

Lappeenranta-Lahti University of Technology LUT

School of Energy Systems

Degree Program in Bioenergy Technology

**MASTER'S THESIS**

**WATER TREATMENT IN PULP AND PAPER MILLS**

Supervisors and examiners: Professor, Esa Vakkilainen

Lappeenranta, 2019

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## **ABSTRACT**

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### **Water treatment in pulp and paper mills**

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The aim of this thesis is to study and compare effect of each certain water quality indicator to water treatment energy consumption. Also, determination of kinds of equipment which are the most exposed of those parameters change. This thesis describes the basic technological processes of water treatment. For research there were considered various Russian water treatment equipment. The graphical dependences of water quality indicators changes and energy consumption were constructed. The results of this study can be used for energy audits at various pulp and paper mills' water treatment installations and in other industries ones such as energy sector for example.

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## **ABBREVIATIONS**

EC – electrical conductivity

H1 – 1st stage H-cation exchange filters

H2 – 2nd stage H-cation exchange filters

MF – Mechanical Filters

NF – nanofiltration filter

OH1 – 1st stage OH-anion exchange filters

OH2 - 2nd stage OH-anion exchange filters

ORP – oxidation reduction potential

RA – Residual Alkalinity

RO – reverse osmosis

TA – Total Alkalinity

TDS – total dissolved solids

TH – total hardness

TSS – total suspended solids

WT – water treatment

## 1. INTRODUCTION

Pulp and paper industry has been actively developing over the past decades but there are matters which can be improved in terms of better performance. Energy consumption is one of the areas where research, development and optimization are required.

It is not a secret that pulp and paper processes demand a lot of water. The water consumption of a modern pulp and paper mill varies considerably depending on the pulp production technology, the availability of water, the sequence of the pulp bleaching process and the restrictions on wastewater discharge.

The pulp and paper industry is one of the major water consumers, as the pulp in the process is washed several times with water and, in addition, water is used to transport the produced at the pulp mill pulp fibrous mass in the course of various technological operations to refine the pulp and feed it to the paper machine, where the mass consisting of 99% water and only 1% fiber (in the terminology used at the paper mill, the mass having a consistency of 1%), can be directed to the sieve conveyor. While the water consumption of old plants is 210 m<sup>3</sup>/t of finished products (paper), modern plants use closed water supply systems, which reduces water consumption and, consequently, the amount of wastewater requiring treatment. For the production of unbleached pulp/paper, from which the facing cardboard is made, the water consumption can be about 40 m<sup>3</sup>/t (for modern plants) and for bleached pulp/paper production process the water consumption exceeds 63-83 m<sup>3</sup>/t [6].

Cellulose is an active absorber of various impurities dissolved in water, so high requirements for the physical and chemical composition of water used in the process are necessity. On the surface of the cellulose there are a large number of functional groups, through which it is able to enter into chemical interaction with dissolved substances, absorbing them from water [18].

Minerals, getting into cellulose, change its mechanical properties, complicate chemical processing, change light sensitivity and other physical and chemical properties of paper and

products obtained on the basis of cellulose. The organic impurities impart color of the cellulose, reduce the whiteness of the paper, impairing the quality of the products.

So, it can be clearly seen that water treatment in pulp and paper industry requires not only a quite big capacity, but high quality of treated water. Consequently, the treatment process is a significant part of internal energy needs of any pulp and paper mill.

Water treatment at industry plants always divided in two significant parts. The first part is raw water treatment and the second one – wastewater treatment. In my thesis I will not consider the wastewater treatment and its contribution in the flow of water used in the plant. The main goal of my thesis is evaluate how raw water indicators affect the energy consumption needed to prepare water to use in the process.

The first step is to consider the main water treatment principles at pulp and paper industry and the exploitable equipment. But before that I would like to give the short review of water quality indicators which could affect the water treatment energy consumption more or less.

## 2. WATER QUALITY INDICATORS

Depending on the purposes of the use of water by different consumers, the concentration indicators needed for the qualitative and quantitative characteristics of water are determined.

Before proceeding to detail the concentration indicators of water quality, we should note that the current scientific, technical and reference books and also production documents (guidelines, manuals, textbooks, operating instructions, etc.) are used to express the concentration such units as Eq/dm<sup>3</sup> or mEq/dm<sup>3</sup>, relating to the equivalent concentration. These units can be met further, especially in the calculations part. Note also that in the expression of concentrations there are differences associated with their expression in relation to dm<sup>3</sup>, kg, L. With the density of the analyzed solution close to 1 kg/dm<sup>3</sup>, the mass and volume concentrations are almost the same.

The most important indicators of water quality for its use for technical purposes are [9]:

- 1) total suspended solids (TSS);
- 2) concentration of dissolved impurities (ionic composition);
- 3) concentration of corrosive gases;
- 4) hydrogen ion concentration;
- 5) technological parameters, which include oxidation, hardness, alkalinity, silica content, conductivity, etc.

Further the closer look at water quality indicators which can affect quality of the final products of pulp and paper facilities is represented.

## 2.1 Silica

Silicic acid gets into the water by dissolving various silicate rocks. The amount of silicic acid in natural waters does not usually exceed 10 mg / L (poorly soluble) [9]. Occurs in water both underground and surface sources in various forms (from colloidal to ion dispersed). Water containing silicic acids cannot be used to high-pressure boilers, as they form a silicate scale on the surfaces.

Silicic acid already at medium pressures has the ability to selective carry-over with dry saturated steam; as the pressure increases, the value of the distribution coefficient for  $\text{SiO}_2$  increases sharply. This is represented in figure 2.1. At the same time, in alkaline boiler water silicon is usually in the form of sodium silicate and only partially in the form of silicic acid. Therefore, the distribution coefficient will be less, the less silicon in the form of silicic acid is contained in the water.

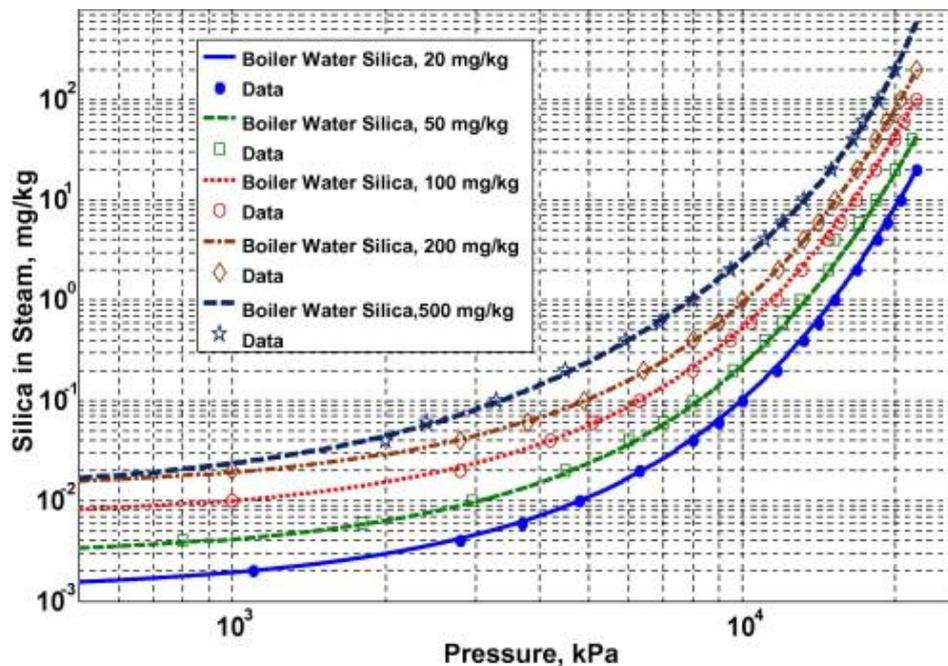


Figure 2.1 Silica carry-over in steam of boilers [9]

So, for normal operation of high-pressure boilers all silica content should be kept at the minimum, rate. More detailed information about amount of silica affordable for stem boilers operation is in the chapter 5.2.

## 2.2 Iron

Iron ions can be found in natural water mainly in the form of  $\text{Fe}^{2+}$  ions, which with most ions do not form insoluble salts and are relatively weak hydrolyzing. At elevated concentrations of dissolved  $\text{O}_2$  (near-surface water layers),  $\text{Fe}^{2+}$  ions are oxidized to  $\text{Fe}^{3+}$  ions, which are easily hydrolyzed to form an insoluble  $\text{Fe}(\text{OH})_3$ , therefore, in surface waters, iron is in colloidal form, and in deep waters - in a truly dissolved state, usually in the form of bicarbonate of ferrous iron  $\text{Fe}(\text{HCO}_3)_2$ . In surface waters, iron is also part of organic compounds. Affecting color of water. [12]

Since iron carbonate as well as calcium carbonate is an insoluble compound and can precipitate under certain conditions. The presence of high concentrations of iron salts in water creates conditions for the development of iron bacteria. It grows on the walls of pipelines in the form of colonies, cause the overgrowing of the working surface and reduce pipes cross-section area. [11]

## 2.3 Calcium and magnesium ions

Calcium and magnesium ions are among the most important impurities of water and largely determine the possibility of its use for various economic purposes, since these ions form insoluble compounds with some anions in the water. When using natural water and the associated change in the initial concentrations of cations and anions, for example, when evaporating or reducing solubility with increasing temperature, it may be the release of insoluble salts of calcium and magnesium on heat-transfer surfaces in the form of a solid phase. The solubility products of some insoluble compounds Ca and Mg at different temperatures are shown in table. 2.3.

Table 2.3 Solubility value of some insoluble compounds depending on water temperature, (mol/dm<sup>3</sup>)<sup>2</sup> [9]

	Temperature, °C					
	20	25	50	80	100	150
Ca(OH) <sub>2</sub>	1.32·10 <sup>-6</sup>	3.37·10 <sup>-6</sup>	5.68·10 <sup>-6</sup>	2.4·10 <sup>-6</sup>	1.47·10 <sup>-7</sup>	2.68·10 <sup>-8</sup>
CaCO <sub>3</sub>	9.51·10 <sup>-9</sup>	6.05·10 <sup>-9</sup>	2.37·10 <sup>-9</sup>	1·10 <sup>-9</sup>	-	1.41·10 <sup>-11</sup>
Mg(OH) <sub>2</sub>	9.40·10 <sup>-11</sup>	6.1·10 <sup>-11</sup>	1.36·10 <sup>-11</sup>	0.51·10 <sup>-11</sup>	0.28·10 <sup>-11</sup>	0.05·10 <sup>-11</sup>
CaCO <sub>3</sub>	-	4.17·10 <sup>-5</sup>	3.87·10 <sup>-5</sup>	2.95·10 <sup>-5</sup>	2.38·10 <sup>-5</sup>	-

More detailed variation of this table was used in the calculation part for constant determining.

## 2.4. Sodium and potassium

Sodium and potassium ions do not form insoluble simple salts with anions contained of natural waters, almost are not hydrolyzed, so they are referred to a group of stable impurities. The concentration of Na<sup>+</sup> and K<sup>+</sup> changes only as a result of evaporation or dilution of natural water, in the water quality analysis the concentration is often expressed as a sum. The content of K<sup>+</sup> is about 5-10 times less than Na<sup>+</sup> (due to the greater prevalence of Na<sup>+</sup> and the predominant adsorption of K<sup>+</sup> by the soil) [12]

Sodium compounds passed into steam can fall into the solid phase under certain conditions forming scale in the turbine. Solubility of different sodium salts in the pair are very different. Solubility of compounds shown in the diagram (figure 2.4, (a)). Sodium sulfate is deposited in the turbine high pressure zone and superheater. Sodium chloride is highly soluble in steam and deposits in turbines usually in the low pressure zone (0.2 - 0.3 MPa). The presence of even a few kilograms of deposits on the turbine blades leads to a significant reduction in efficiency (figure 2.4 (b)). [3]

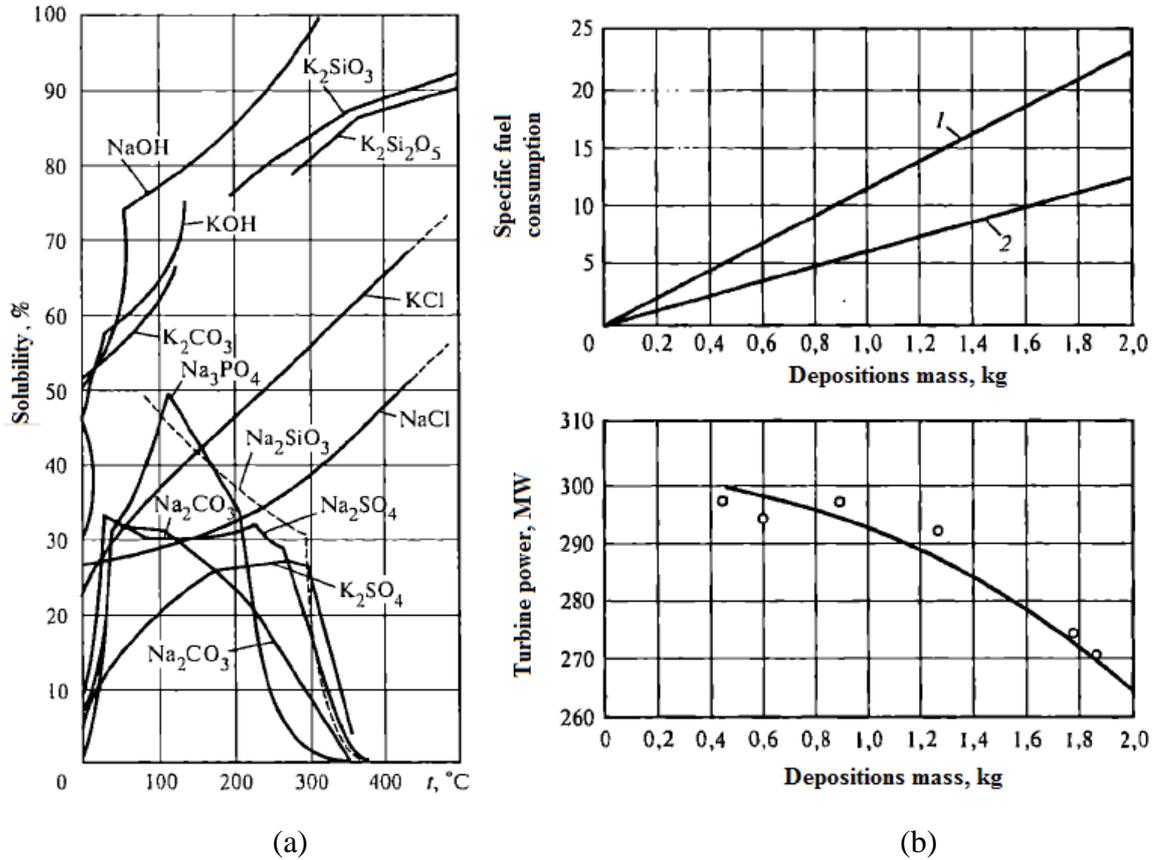
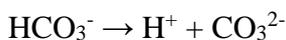


Figure 2.4 (a) Dependence of solubility of various substances on temperature, (b) Functions of specific fuel consumption and turbine power of depositions mass. [3]

## 2.5 Carbonic acid

Anions of carbonic acid ( $\text{HCO}_3^-$  and  $\text{CO}_3^{2-}$ ) are ones of the most important anions in natural waters, which determine the behavior of various impurities in them, as well as in the technological processes of water treatment. Natural water contains several forms of carbonic acid, namely,  $\text{CO}_2$ ,  $\text{H}_2\text{CO}_3$ ,  $\text{HCO}_3^-$  and  $\text{CO}_3^{2-}$ . Usually the concentration of carbonic acid expressed in terms of  $\text{CO}_2$ , as in pure water the concentration of  $\text{H}_2\text{CO}_3$  is about 0.2% of total quantity of dissolved  $\text{CO}_2$ . In water carbonic acid dissociates through two steps to forms bicarbonate and carbonate ions:



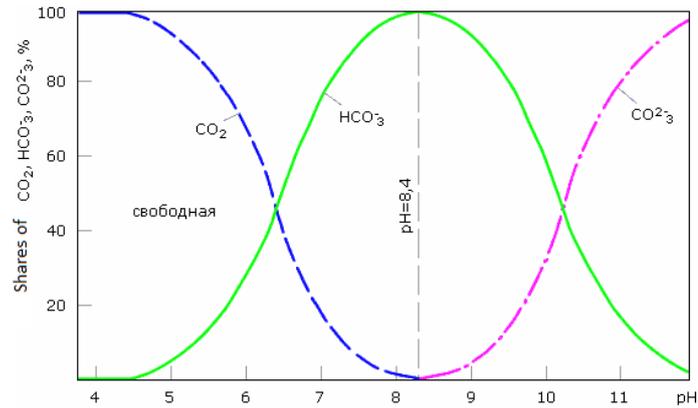


Figure 2.5 Graph of the ratio of molar concentrations of different forms of carbonic acid depending on pH at 25°C [9]

Water alkalinity is determined by the amount of hydroxyl ions and anions of weak acids — carbon, as well as bicarbonate and carbonate ions contained in water. As a result of the reaction with calcium and other cations, carbonic acid ions make the insoluble compounds, forming scale on the heat-transfer surfaces, reducing thermal conductivity. In particular, CaCO<sub>3</sub> is formed.

The presence of carbon dioxide leads to an increase in the corrosion rate primarily due to increased hydrogen depolarization and deterioration of the protective properties of the resulting film. In the presence of free carbon dioxide in the solution, corrosion of steel can occur simultaneously with oxygen and hydrogen depolarization.

## 2.6 Sulfate

When moisture condensates in the atmosphere, significant amount of sulfur oxides and other products contained in the flue gases dissolves in the condensate. The concentration in the atmospheric moisture is around 10 mg/dm<sup>3</sup> [11]. Water, seeping through the soil, contacts with various mineral salts and organic substances, dissolves or mechanically captures them. With the simultaneous presence of oxygen, organic substances and microorganisms (bacteria) in the water surface layers, conditions are created for the conversion of sulfur to sulfuric acid. Being in the water and carried over to steam, sulfuric acid ions cause corrosion, as well as the formation of CaSO<sub>4</sub> which forms a scale when precipitates on heat-transfer surfaces.

## 2.7 Chloride

The goal of ions removal – reducing corrosion and deposition. The reduction of the corrosion (electrochemical) is achieved by reducing the ORP (and EC as a consequence) of water. Even if there is a potential difference in the metal due to deposits, or irregularities in the metal, the EC of medium affects the corrosion rate, because electrons will be removed from the metal surface, intensifying the removal of metal ions, on the principle of Le Chatelier. And also it leads to prevention of formation of deposits (less ions – less deposits). And chloride is a strong depolarizer (removes electrons and intensifies corrosion).

## 2.8 TSS

There are plenty of different materials included in this term, the table below represents the main of them and their sizes.

Table 2.8 Sizes of suspended solids [12]

Suspended solids	Colloidal particles	Thin mud	Mud	Sludge	Sand		
					Small	Medium	Large
Size, mm	$10^{-6} - 10^{-4}$	$10^{-3} - 10^{-4}$	$27 \cdot 10^{-4}$	$5 \cdot 10^{-2} - 27 \cdot 10^{-3}$	0.1	0.5	1

Presence of these impurities in the water leads to their sedimentation and deposition on heat-transfer surfaces if there is no suitable water purification. But actually the main problem related to size of particles and their properties. It impacts to filters of next stages of water treatment after pre-treatment stage (their filter cycle duration and consequently the energy and chemicals consumption).

## 2.9 Oxidability

Oxidability is a value that characterizes the content of organic and mineral substances in water that are oxidized (under certain conditions) by one of the strong chemical oxidizers. This indicator reflects the total concentration of organic compounds in water. The nature of organic substances can be very different - and humic acids of soils, and complex plant compounds, and chemical compounds of anthropogenic origin.

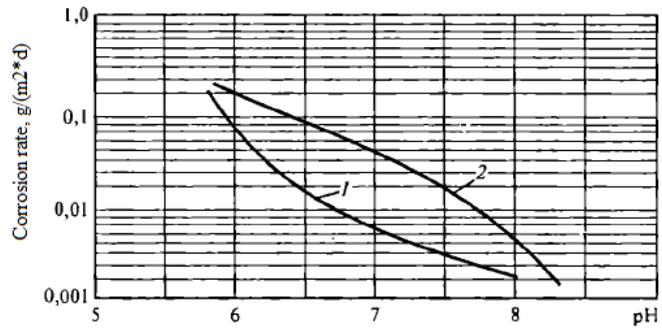
The negative impact of organic water impurities is due to the fact that these impurities can be oxidized during the operation of water, the result of this process is the formation of a number of organic acids that destroy the metal parts of the equipment.

## 2.10 pH

The concentration of hydrogen ions in the water is one of the most significant external factors affecting the corrosion rate, since the properties of the protective films depend on the pH of the medium. With increasing temperature, the role of pH increases due to the probability of depolarization processes. The nature of the relation between the corrosion rate of the metal and the pH of the medium is also determined by the chemical properties of the protective films formed during corrosion.

Depending on the properties of the metal on its surface are formed:

- amphoteric type film, soluble in acids and alkalis
- the alkali type of film. Such films become more resistant in an alkaline medium (with increasing pH)
- the films are not formed on the surfaces of noble metals; corrosion is negligible
- copper occupies an intermediate position, since the amphoteric properties of the film are weak and appear only in an alkaline medium (figure 2.7 (a))
- the influence of pH on the corrosion of low-alloy and carbon steels is particularly large (figure 2.7 (b)).



1 ---  $C_{O_2} = 10 \div 20 \text{ } \mu\text{g/kg}$ ; 2 ---  $C_{O_2} = 550 \div 650 \text{ } \mu\text{g/kg}$

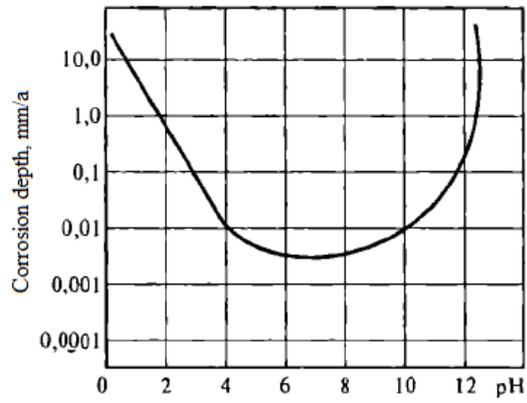


Figure 2.7 (a) Effect of pH on the corrosion rate of copper in water (b) carbon steel [3]

### **3. WATER TREATMENT EQUIPMENT AT PULP AND PAPER MILLS**

At modern pulp and paper mills advanced water treatment equipment is used. There are three ways to deal with impurities in raw water:

- Ion-exchange technology
- Membranes
- Thermal methods

Last time trends at the water treatment equipment market more and more inclines in favor of membrane technology as more efficient, cheap, environmental friendly (chemicals free) technology. Now, even existing water treatment units at Finnish paper mills are considering the possibility of switching to membrane technology [8]. But the biggest share of the market and already built facilities are equipped with ion-exchange filters and this particular way to deal with water treatment will be considered below and used for calculations in chapter 5.

Independently on type of water treatment, in the begging of any scheme the pre-treatment is placed. As it was said earlier at chapter 2.8, suspended solids affects the operation of the main part of water treatment, so before supply water at membranes or ion-exchange filters the biggest impurities should be sedimented at clarifiers or removed by located next along the scheme mechanical filters.

After considering the pre-treatment of water, we will consider the final stage of water preparation associated with a change in its ionic composition, up to the complete removal of dissolved impurities, implemented by ion exchange technology, as well as membrane or thermal methods.

### 3.1 Raw water pre-treatment

Clarification of water, i.e. removal of suspended solids and colloidal impurities from it, is produced by coagulation. If necessary, depending on the quality of the water and the further scheme of its treatment, simultaneously with the clarification, the alkalinity of the water is reduced, implementing its partial softening, the removal of silicic acid compounds, etc. For these purposes other methods of water pretreatment are used – liming, magnesium desiliconizing, etc. Usually combined with coagulation. Coagulation, liming, magnesia desiliconizing of water and other methods form a group of *sedimentation* methods, so called because the substances removed from the treated water are released in the form of sediment, the formation of which is achieved by the introduction of certain reagents into the treated water. Therefore, methods of sedimentation, also called *chemical* methods of water treatment.

#### 3.1.1 Coagulation

Colloidal systems in natural waters have aggregate stability, i.e. stability of dispersion (stability of the size of colloidal particles). Aggregate stability at small sizes of the colloidal particles facilitates the sedimentation stability, i.e., constancy of the concentration of the colloidal particles throughout the solution volume.

Colloidal particles stick together when the loss of aggregative stability occurs. Coagulation is physicochemical process of enlargement of colloidal particles due to their adhesion under the action of intermolecular attraction forces, followed by their release from water. The main purpose of coagulation is removal of organic impurities from water. In addition, during coagulation next processes happen: the reduction of concentration of particulate impurities and color, improve the conditions of deposition of calcium carbonate and magnesium hydroxide during reagent method of water softening.

During treatment of feed water, mutual coagulation of heterogeneous dispersed systems – *heterocoagulation* – is used. To do this, a *coagulant* is added to the purified water, i.e. a solution of mineral salt capable of forming an artificial colloidal solution. Because colloidal

particles of natural waters usually have a negative charge, mineral salt is chosen in such way the particles of the artificial solution formed by this salt have a positive charge. When coagulant is added to the treated natural water, the neutralization of the negatively charged colloidal particles occurs in natural water with the positively charged colloidal particles of coagulant, their adhesion and enlargement in flakes and sedimentation.

During treatment of natural water from organic impurities as a coagulant can be used: aluminum sulfate  $\text{Al}_2(\text{SO}_4)_3 \cdot 18\text{H}_2\text{O}$ , iron sulfate  $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$  and aluminum oxychloride  $\text{Al}_m(\text{OH})_n\text{Cl}_{3m-n}$ . Sulfuric iron is used as a coagulant when combining the processes of coagulation and liming. At  $\text{pH} > 8$ , aluminum in aqueous solution forms soluble aluminates  $\text{AlO}^{2-}$ . At  $\text{pH} < 4.5$ , the hydrolysis of aluminum sulfate almost does not happen. Divalent iron hydrolysis occurs very slowly at  $\text{pH} < 8$  and iron hydroxide flakes  $\text{Fe}(\text{OH})_2$  is formed only at  $\text{pH} > 9$  [5].

The quality of coagulated water depends on the composition of the source water and compliance with optimal coagulation conditions. In coagulated water, the content of organic impurities and suspended solids decreases; alkalinity decreases, concentrations of carbon dioxide and sulfate ions increase. With the established technology of the process, the following indicators of the quality of coagulated water are usually provided [2]:

- The residual permanganate oxidability is 30 – 40 % of the initial value
- Silicon content is reduced by 60 – 90 %
- The concentration of dissolved carbon dioxide is increased by the dose of coagulant
- The concentration of sulfate ions increases by the dose of coagulant
- Alkalinity is reduced by the dose of coagulant
- The total hardness remains unchanged, but redistribution of hardness occurs
- The content of suspended solids is 1-2 mg/L
- The transparency of water more than 30 cm

The work of the clarifier for coagulation is shown with the example of the clarifier ЦНИИ-2. The scheme of the clarifier is shown in figure 3.1.1.

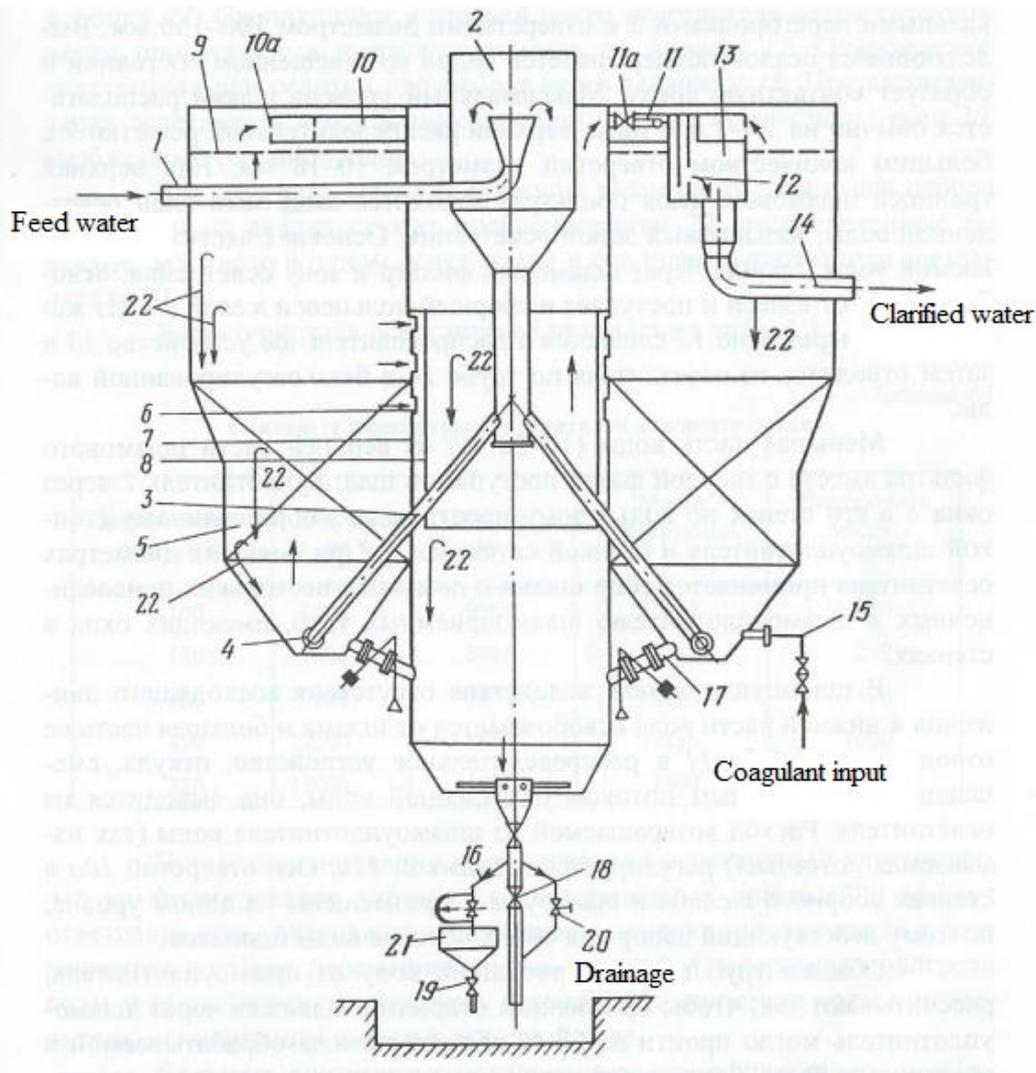


Figure 3.1.1 Scheme of clarifier for coagulation ЦНИИ-2 [2]

The treated water is supplied through the pipeline 1 to the air separator 2 and then through the distribution pipes 3 ending with nozzles 4, enters the lower part of the clarifier. Here, through the pipeline 15, a coagulant solution is supplied with a dosing pump. The mixing of water and reagent is achieved by the tangential injection of water through the nozzles, giving it a rotary motion, which is then extinguished by vertical partitions 5 with holes with a diameter of 100-150 mm. Produced sediment is supported by the water in suspended state and forms a contact environment. The maximum level of slurry is usually 1.4 - 1.6 m below the upper distribution grid 9 with a large number of holes with a diameter of 10-18 mm. Above the upper boundary of the slurry layer (filter) is a protective layer of clarified water, called the clarification zone. The main part of the treated water, passing through the slurry filter and the clarification zone, is released from the suspension and enters the collecting ring

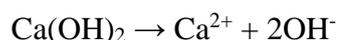
chute 10. From the chute, water through the window 12 is drained into the distribution unit 13 and then discharged from the clarifier through the pipe 14 into the coagulated water tank.

A smaller part of the water (10 - 20 %) from the top of the slurry filter, together with the solid phase, enters the sludge compactor 7 through windows 6 in its walls through the annular space formed by the wall of the sludge compactor and the wall of the container 8. In the sludge compactor due to the lack of upward movement in the lower part the water gets rid of sludge and most of it is discharged through the pipe 11 in the distribution device, where it is mixed with the rest of the flow of clarified water and it is removed from the clarifier. Return water flow is regulated by the valve 11a.

Sediment that accumulates in the sludge compactor below the edge of the container 8 is removed by the pressure of the overlying layers with a height of 1.5 - 2 m. Thickened precipitate is removed through line of continuous blowdown 16 to the drain 19. Crane of continuous blowdown is tared in relation to filling of the funnel 21. The sand accumulated in the lower part of the clarifier is periodically passed into the sludge compactor along lines 17. Emptying the clarifier during the audit is carried out through the valve 18. When automating the clarifier, continuous purge is carried out through a 20 crane equipped with a servo drive. To control the quality and level of the slurry layer and to take water samples for analysis, samplers 22 are distributed in height, their number in one clarifier is 6-10.

### **3.1.2 Clarification with coagulant and lime**

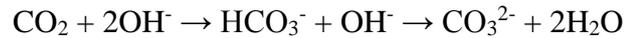
The main purpose of liming is to reduce the alkalinity (decarbonization) of the raw water, which is achieved by increasing the pH value above 9 with simultaneous withdrawal (deposition) of carbonate ions formed as the insoluble compound  $\text{CaCO}_3$ . To do this, lime is introduced into the treated water in the form of solution or suspension. As a result of lime supply, the concentration of  $\text{Ca}^{2+}$  and  $\text{OH}^-$  ions in the treated water increases [2]:



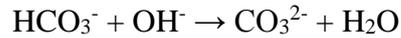
This leads to a shift of the carbon dioxide equilibrium and simultaneous increase of pH.

In General, the liming process consists of the following stages:

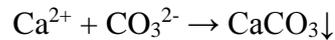
- Interaction of OH<sup>-</sup> ions with hydrated carbon dioxide molecules:



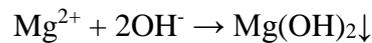
- Interaction of OH<sup>-</sup> ions with bicarbonate ions present in water and determining its alkalinity:



- Formation of the solid phase (crystallization) of CaCO<sub>3</sub> from CO<sub>3</sub><sup>2-</sup> ions and Ca<sup>2+</sup> ions contained in the source water and introduced with lime because excess of the solubility product of calcium carbonate:



When the lime dose is greater than it is necessary for the transfer of free carbon dioxide and bicarbonate ions into carbonate ions, excess concentration of hydroxyl ions appears in the water and the solubility product of Mg(OH)<sub>2</sub> can be exceeded. In this case, the decrease of the magnesium hardness of the water occurs:



In operating conditions, the result of liming is usually assessed by the following indicators: residual alkalinity, stability, content of suspended solids, oxidability, hardness, iron content. How clarifier СКБ ВТИ-1000 for combined coagulant and lime dosing works is shown in figure 3.1.2

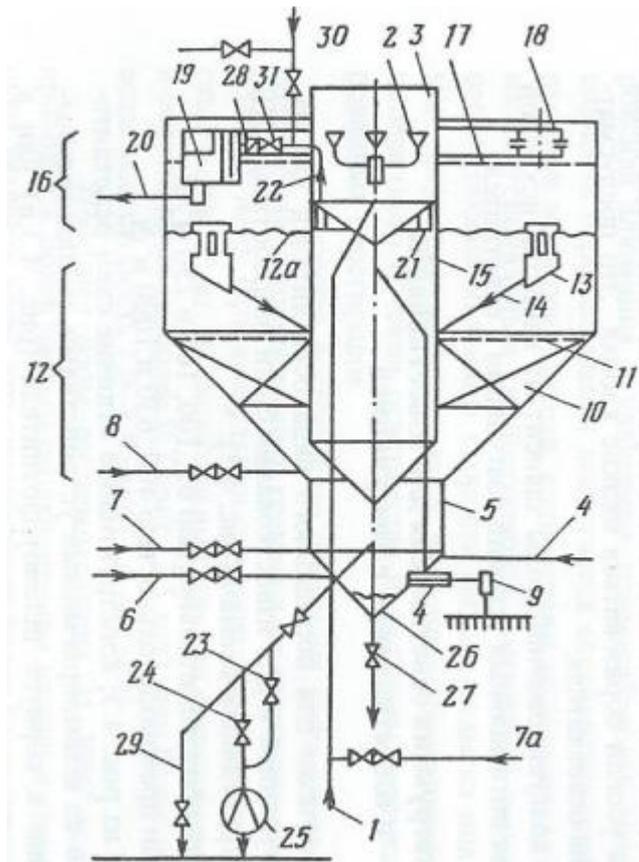


Fig. 3.1.2 Scheme of the clarifier СКБ ВТИ-1000 for combined coagulant and lime dosing [2]

Such clarifier operates as follows. The raw water 1, heated to a predetermined temperature, is fed into the air separation funnels 2 of the air separator 3, in which it gets rid from the air bubbles. From the air separator through the downpipe through a tangentially directed inlet with a regulating device 9, the initial water enters the lower part of the apparatus 5 - a mixer of water and reagents. If the washing water of the mechanical filters is used, this water is sent to the mixer through the pipeline 4. Lime milk 6, a solution of coagulant 7 and flocculant 8 enter the mixer through the radially directed pipelines located at different levels. In addition, the inlet for the introduction of coagulant 7a into the source water pipeline is provided. The complex of chemical reactions completes in the mixing zone, at the exit from which the separation of the interaction products in the form of flakes begins. They increase in volume and are detained by the upward movement of water. The rotational motion given to water by tangential insert is extinguished by vertical partitions 10 and horizontal partition 11, which have holes with a diameter of 100 - 150 mm.

The upper limit of the suspended slurry, forming contact environment, in the clarifier 12 is at the level of the slurry-collecting windows 13 of the slurry compactor 15. The excess sludge is continuously removed, for this purpose the part of the total water flow is removed from the contact zone in the slurry compactor. After the suspended slurry layer, the water passes through the clarification zone 16, the upper distribution grid 17 and merges through the deposits into the chute 18. Next, the water enters the distribution device 19, is mixed with clarified water coming from the sludge compactor, and through the pipeline 20 is discharged into the limed water tank. Sludge received with a cut-off, settles in the lower part of the sludge compactor and through the pipes 23 (continuous blowdown) and 24 (periodic blowdown) is removed from it through the measuring spacer 25.

For emptying and filling of the slurry compactor, a pipeline 29 is provided. The water clarified in the slurry compactor is collected by the perforated collector 21 and discharged through the pipeline 22 to the distribution device 19.

On the discharge pipe there is a throttle valve 28, usually controlled remotely, which regulates the flow of water coming through the slurry compactor. On the same pipeline, a valve 31 is installed which is open during the operation of the clarifier and closes when the collector of the slurry compactor is washed with water supplied through the pipeline 30, through the same pipeline the water fed for washing the chute 18 and the grid 17. For the discharge of large settling sludge and sand coming from the feed water, a sump 26 is used, from which big particles are periodically removed through the pipeline 27, it is also used to empty the clarifier.

### **3.1.3 Pre-treatment scheme**

The difference between auxiliary equipment of two described above clarifier types is only the presence of analogous set of pumps, tanks, mixers and reagent cells for lime as for coagulant. Below the figure 3.1.3 presents such scheme for coagulant.

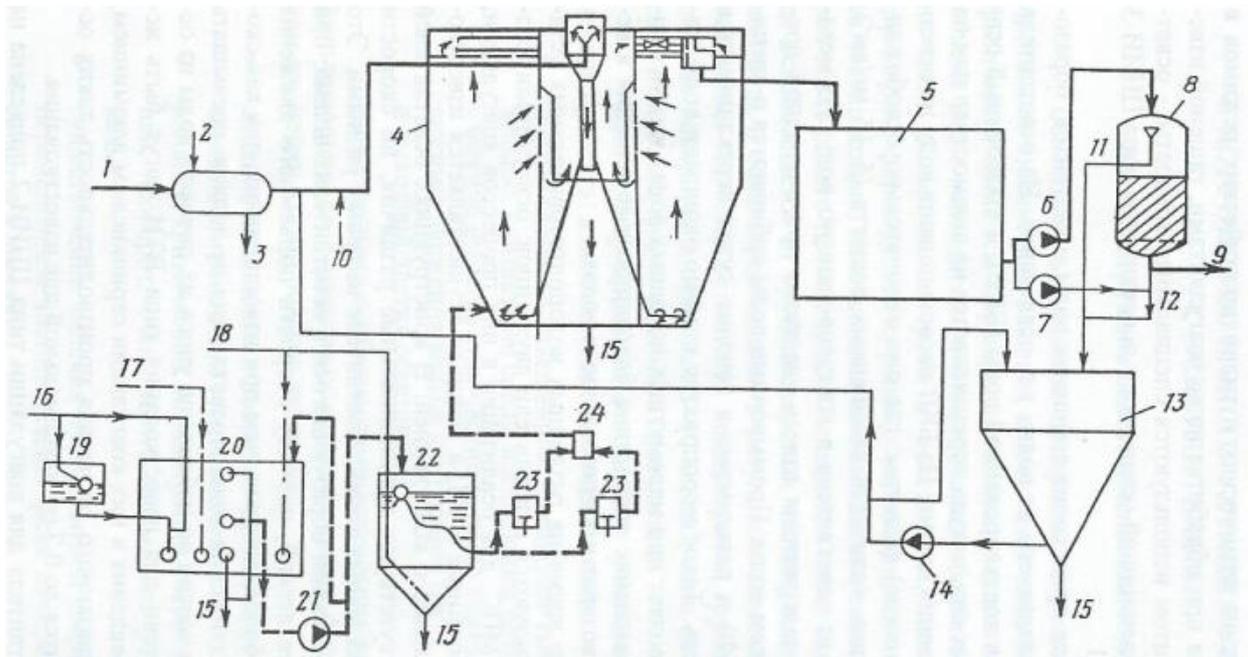


Figure 3.1.3 Scheme of coagulation installation [2]

1 - feed water; 2 - heating steam; 3 - condensate; 4 - clarifier; 5 - tank of coagulated water; 6 – pump of coagulated water; 7 pump of the loosening rinse of mechanical filter; 8 - mechanical filter; 9 - clarified water; 10 – insert of agent (alkali) to create the required pH; 11 – discharge of loosening rinse; 12 - discharge of filtrate; 13 – tank for backwashing collecting; 14 - pump for backwashing to the clarifier; 15 - blowdown; 16 - technical water; 17 - hot water or steam to dissolve the alumina; 18 - compressed air for mixing; 19 - tank of constant level; 20 - cell of wet storage of coagulant; 21 - the pump for coagulant solution; 22 – measuring tank of coagulant; 23 - dosing pump of coagulant; 24 - air cap

### 3.2 Ion-exchange technology

Having considered the provisions determining the technology of removal of suspended solids and colloidal impurities from natural waters and condensates, we note that pre-treatment of water is insufficient in the preparation of water.

The idea of ion exchange is the ability of special materials (ionites) to change the ion composition of the treated water in the desired direction. Ionites are insoluble high-molecular substances, which due to the presence of special functional groups are capable of ion exchange reactions. In other words, ionites are able to absorb positive or negative ions from the solution in exchange for equivalent amounts of other ions contained in having a charge of the same sign ionite. Cationites and anionites are distinguished by the sign of charge of

exchanging ions. The ability of the resins to exchange ions with a solution is determined by their structure. Ionites consist of an insoluble solid base (matrix), obtained most often by copolymerization of the initial products: styrene and divinylbenzene and added in amount of about 8% for cross-linking polystyrene. The spatial grid of hydrocarbon chains obtained in the form of grains is a matrix. When it is placed in water, it is able to increase its volume by 1.1 - 2.0 times due to interaction with polar H<sub>2</sub>O molecules, which makes it possible for mutual diffusion of exchanging ions after the synthesis and transformation of the matrix into ionite.

The abbreviations presented below correspond to the filters of Russian production, but the principle is widely used around the world and it is pretty the same. Ion-exchange technology of water and condensates treatment is performed in the ion-exchange filters of the following types [5]:

- 1) ФИПа I – parallel-current ion-exchange filters of water treatment first stage;
- 2) ФИПа II – parallel- current ion-exchange filters of water treatment second stage;
- 3) ФИПр – counter-current ion-exchange filters;
- 4) ФИПр-2П – dual-flow with countercurrent ion-exchange filters;
- 5) ФИСДНр – mixed-bed ion-exchange filters with the outer (external) regeneration;
- 6) ФИСДВр – mixed-bed ion-exchange filters with internal regeneration;
- 7) ФР - filters regenerators for ФИСДНр with external regeneration.

Each certain filter type will be considered more detailed throughout next chapters, as well as main schemes of how they work.

### **3.2.1 Parallel-current ion-exchange filters**

In figure 3.2.1 the design of the parallel-current ion-exchange filter. Filter consists of a cylindrical case with elliptical upper and lower bottoms, upper and lower drainage and distribution devices, pipelines with fittings and measuring devices located on the front of the filter. The bottom distribution device, which serves to hold the resin, removal of filtrate and the distribution of loosening water, is mounted on a concrete pad. The upper distribution device is used for uniform distribution of the source water and regeneration flows through

the ionite layer, as well as for the removal of loosening water. Connected to the filter system of pipelines and valves ensures all the necessary technological operations during its operation.

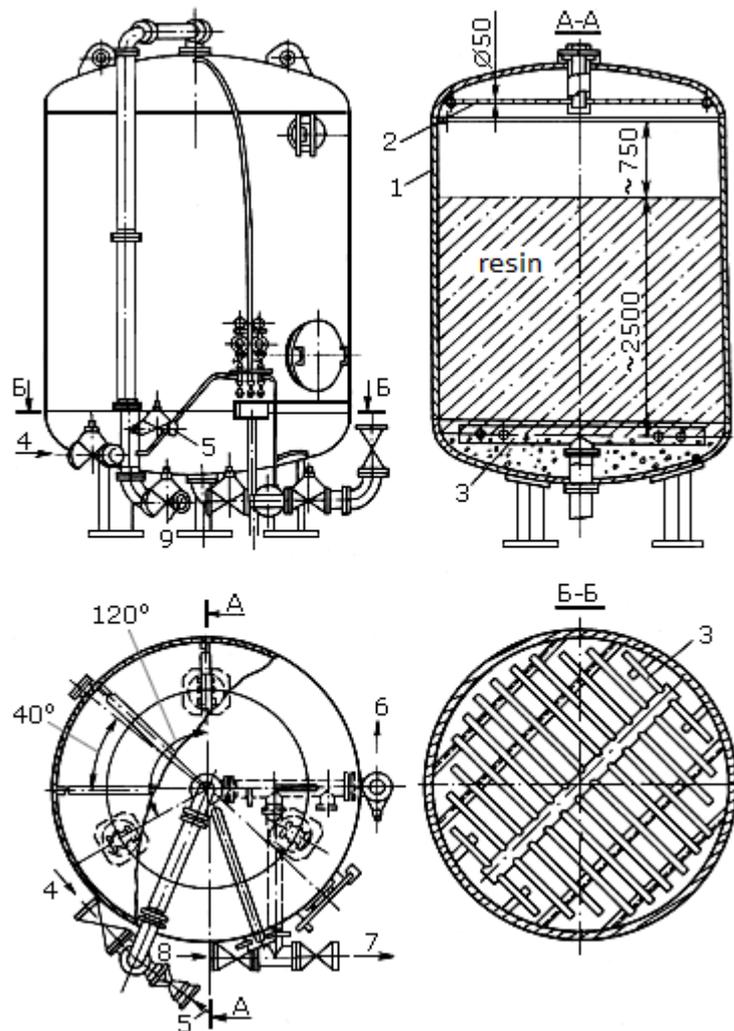


Figure 3.2.1 Design of the ФИПа type filter [9]

1 – case; 2, 3 – upper and lower drainage-distribution device; 4 – supply of feed water; 5 – supply of regeneration solution; 6 – output of filtrate; 7 – discharge of the regeneration solution to the washing water; 8 – supply of water for loosening; 9 – output of loosening water

The operation of ion exchange filters consists of the following operations, which are the complete filter operating cycle [9]:

- 1) loosening
- 2) regeneration (supply of the regeneration solution)
- 3) washing
- 4) filtration

Operation "loosening" is necessary to remove suspended solids accumulated in the ionite layer formed due to the destruction of ionite grains, the presence of which leads to increase in the pressure drop in the ionite layer. In addition, the loosening, carried out by an upward flow of water, decompresses the layer, facilitating access for regeneration solution to the ionite grains. Because loosening the layer of the ionite expands to 30 – 40 % but the working part of ionite must not leave the filter. Usually, loosening is carried out with previous regeneration washing water for 20 minutes with intensity of  $2.5 - 3.0 \text{ dm}^3/(\text{s}\cdot\text{m}^2)$ .

Regeneration of each filter is carried out with a solution of certain concentration of the corresponding reagent. The rate of regeneration solution passing depends on the technological purpose of the filter. Thus, in the regeneration of Na-cationic filter regeneration solution NaCl concentration of 7 – 8 % is passed at a speed of 4 - 6 m/h, the same rate is maintained by passing the NaOH solution concentration of about 4% through H-anionic filters. When regenerating H-cationic filters the  $\text{H}_2\text{SO}_4$  solution concentration of 1.0 – 1.5 % is fed with the rate of not less than 10 m/h to avoid "gypsuming" of cation. To save reagents, the last portions of the regeneration solutions are usually taken to the tank for reuse in the subsequent. In complete desalination schemes, the NaOH regeneration solution is first passed through strong base exchanger and then through weak base one, which makes it possible to create the required alkali excess for second stage filters and significantly save the reagent. Reagent solutions are usually prepared on their own filtrate for each group of filters. Depending on the flow rate of the reagent and its concentration in the solution, the duration of its supply is between 15 to 30 minutes.

After supply of regenerating solution stops, washing of the ionite layer from the products of regeneration and residues of regenerating solution starts. Usually there are two stages [9]:

- 1) through the line of reagent after it stops with the simultaneous rinsing
- 2) with the initial water for this filter.

The last portions of the washing water are collected in the tank for later use during loosening or preparation of the regeneration solution, thereby saving water for internal needs. Washing of Na-cationic filters is stopped when the specified hardness value is reached. H-cationic filters of 1 stage are washed till acidity exceeds the average for the operating cycle by 0.1 mEq/dm<sup>3</sup>, as for anionite filters of the 1<sup>st</sup> stage the specified alkalinity of the filtrate and the content of chlorides in it are not more than 1 - 2 mg/dm<sup>3</sup>. For 2<sup>nd</sup> stages the salt content of after-wash water less than 2 - 3 mg/dm<sup>3</sup> or silicon content less than 0.02 mg/dm<sup>3</sup>.

### **3.2.2 Mixed-bed filters**

As it was previously said there are two types of mixed-bed filters:

- 1) with the outer (external) regeneration
- 2) with internal regeneration

The difference between them is only the way they are maintained (regenerated). Main statements [12]:

- Load: mixture (from 2:1 to 1:2) of high-acid cationite and a strong base anionite
- Reduced antiionic effect
- Residual conductivity less than 0.2 μSm/cm

It is not possible to regenerate the mixed layer of ionites without previous separation of the layer of cation exchange resin and layer of anion exchanger. This separation, and therefore regeneration, can be carried out in two ways, each of which predetermines the required design of the filter. According to the first method, internal regeneration of the mixed layer is used in water treatment installations schemes with low capacity. To implement this method, the filter must be equipped with an average drainage system (Fig. 3.2.2.1). Separation of the ionite mixture is carried out in the filter itself, and after separation, the

anionite is located in the upper part, and the cationite in the lower, strictly under the middle drainage system (as it is shown on the left side). Regeneration is carried out by supplying an alkali solution from the top, and the acid from the bottom with simultaneous removal of regeneration solutions through the middle drainage system. After the loosening of ionites layers the additional washing of the resins happens through the regeneration lines and then they are mixed with compressed air. In mixed-bed filters the filtration rate is limited by 50 m/h to avoid damage to the average drainage system.

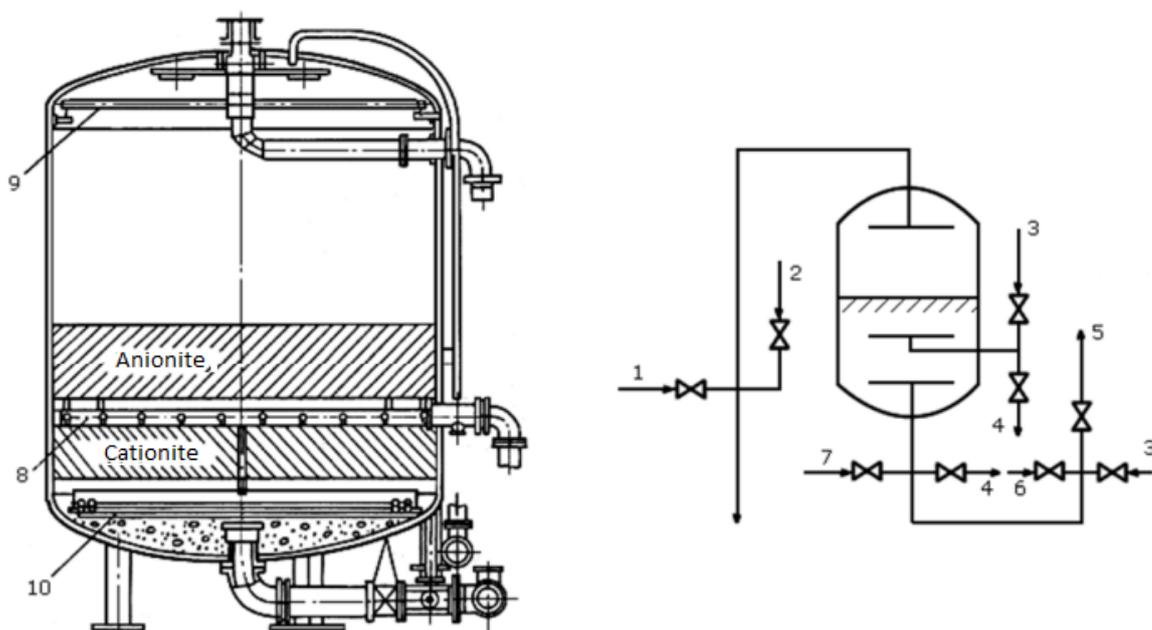


Figure 3.2.2.1 Design and concept of mixed-bed filter with internal regeneration [9]

1 – supply of feed water; 2 – supply of regenerative solution of alkali; 3 – supply of demineralized water; 4 – drainage; 5 – filtrate outlet; 6 – supply of regenerative acid solution; 7 – supply of compressed air; 8 – medium drainage system; 9, 10 – upper and lower drainage systems

The second method is a method with outer (external) regeneration (Fig. 3.2.2.2). Mixed ionites are discharged from the ФИСДНр with stream of water in the first filter regenerator, which separating the mixture on cation exchanger and the anion exchanger. The hydraulic method based on the difference between the specific masses of the resins. Then anionite is sent to the second filter-regenerator by hydro-loading. After separate regeneration, the cation exchanger and the anion exchanger are transported to the mixed-bed filter, mixed with

compressed air and further washed until nearly neutral state and then filter ready to work. With this method of regeneration ФИСДНр can be operated at speeds filtering up to 100 m/h as part of the systems of turbine condensate purification. Organization of external regeneration eliminates the supply of regeneration solutions of acid and alkali in the treated condensate [9].

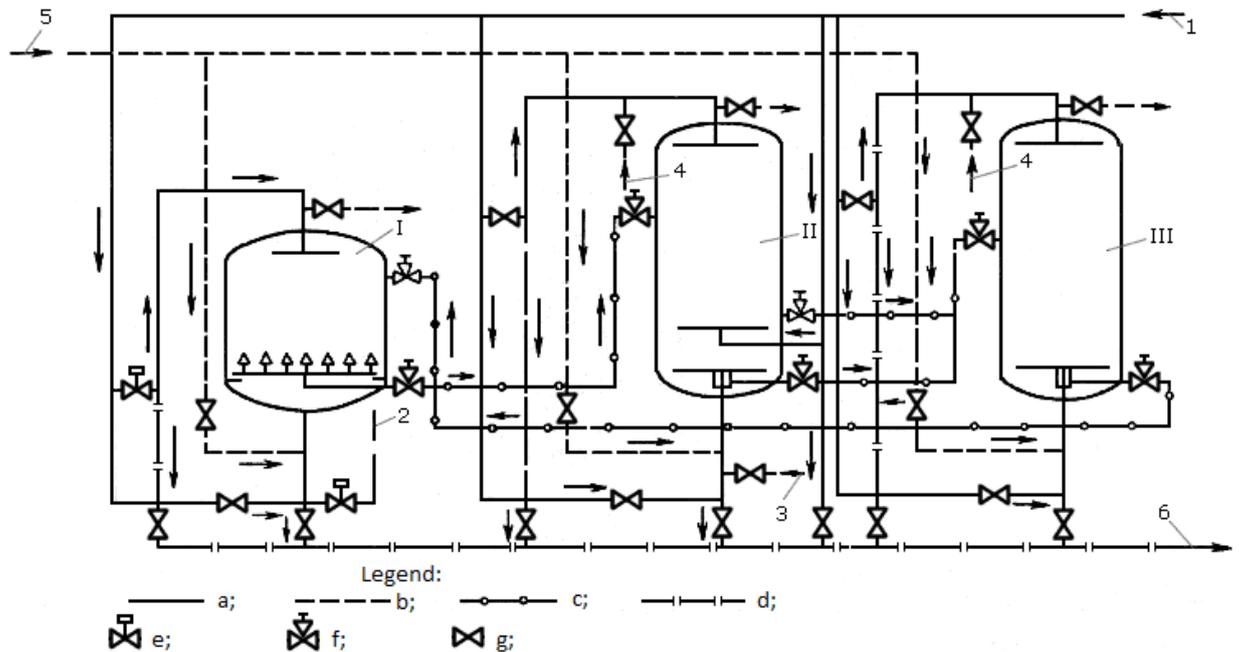


Figure 3.2.2.2 Schematic diagram of the installation of mixed-bed filters with external regeneration [9]

I – mixed-bed filter; II – the first filter regenerator; III – a second filter-regenerator; 1 – supply of feed condensate;  
 2 – outlet of treated condensate; 3 – inlet of regeneration solution  $H_2SO_4$ ; 4 – supply of regeneration solution of  $NaOH$ ; 5 – compressed air; 6 - discharge to the neutralization of the wastewater; a – feed water; b – air; c – water for ion-exchange materials unload; d – drainage; e – damper with actuator; f – valve hose; g – valve

### 3.2.3 Technological schemes of ion-exchange installations

Selection of schemes for the preparation of make-up water is determined by the quality of the feed water and the required quality of the treated water, as well as the conditions of efficiency, reliability and amount of discharged impurities, formed during the water treatment operation, into water bodies. A set of applied schemes is shown in Fig. 3.2.3. Schemes 1 - 7 are applied to water softening in relation to boilers of low and medium

pressure, and some of them, in particular, with Na-filters are used for feeding of thermal networks of the closed and open types.

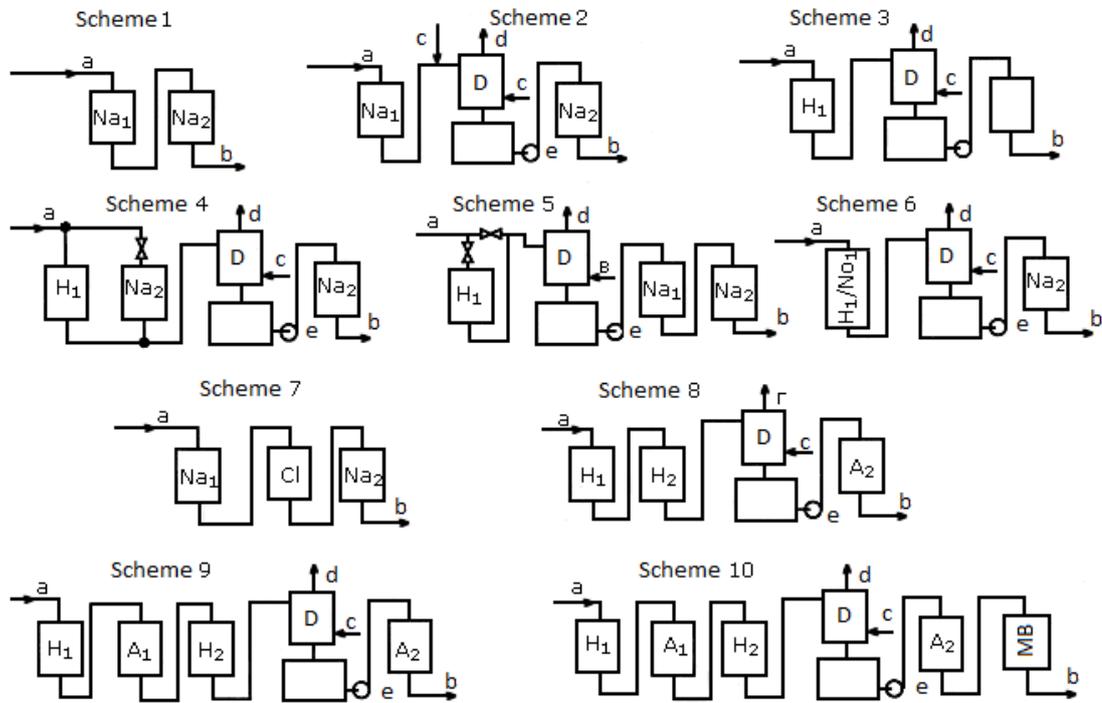


Figure 3.2.3 Concepts of ion-exchange water treatment installations of boilers feed water and feed water for district heating [9]

Na<sub>1</sub> and Na<sub>2</sub> – sodium-cationite filters of 1<sup>st</sup> and 2<sup>nd</sup> stages; H<sub>1</sub> and H<sub>2</sub> – hydrogen-cationite filters 1 and 2 stages;

A<sub>1</sub> and A<sub>2</sub> – anionite filters 1 and 2 stages; Cl – anion-exchange filter of Cl-form; MB – mixed-bed filter; D – degassed; a – supply of clarified water; b – the output of the filtrate; c – the air for degasser; d – the release of carbon dioxide from degasser; e – intermediate pump

For the preparation of chemically demineralized water, a sequential combination of H-cationization and OH-anionization are performed. According to the degree of removal of ionized impurities from the water, partial (scheme 8), deep (scheme 9) and complete chemical desalination are performed, which differ in the number of treatment stages and, accordingly, the quality of demineralized water. Note that the location of the degasser behind the H<sub>2</sub> filter in schemes 9 and 10 is not unambiguous. Its place in figure 9 and 10 provides the deepest removal of carbon dioxide from acidic water, but requires the installation of acid-resistant pumps. The transfer of the degasser location behind the A<sub>1</sub>-filter simplifies the corrosion protection of the inner surface of the degasser but it increases the ion load to the strong base anionite in the A<sub>2</sub> and mixed-bed filters.

### 3.3 Membrane technology

The tightening of requirements for wastewater of the WT determined the development of non-reagent water purification methods, among which membrane methods such as reverse osmosis (hyperfiltration), ultrafiltration and electrodialysis are the most developed for practical use. The basis of all membrane technologies is the transfer of impurities or water through the membrane. The nature of the forces causing such transfer, and the structures of the membranes in these processes are different. During hyper- and ultrafiltration membranes must pass water molecules, retaining the maximum amount of ions and molecules of impurities. When using electric forces in the electrodialysis method, the membranes must be ion permeable and must not allow water molecules to pass through.

Compared with other membrane methods have the following advantages [6]:

- 1) the absence of phase changes in the separation of impurities from the solution allows to minimize the energy consumption for the processes;
- 2) if we exclude timespans for the membranes cleaning, the processes are continuous;
- 3) they can be used without additives of chemical reagents, if the last are entered, the quantities are minimum;
- 4) no special heating of the treated water is required;
- 5) apparatus for the implementation of membrane processes are relatively simple in design and have no moving parts;
- 6) the energy consumption required for the operating the membrane technologies usually does not exceed 4 - 6.5 (kWh) per 1 m<sup>3</sup> of treated water;

Technologies of reverse osmosis and ultrafiltration are considered more detailed throughout next chapters.

### 3.3.1 Reverse osmosis and ultrafiltration technology

The concept of "reverse osmosis" shows the reversibility of natural (direct) osmosis. The latter is characterized by a spontaneous transition of the solvent through a semipermeable membrane into the solution. The illustration of the processes of direct and reverse osmosis scheme given in (Fig. 3.3.1.1). If clean water and an aqueous solution of an inorganic substance are placed in two compartments on either side of a semipermeable membrane capable of passing only H<sub>2</sub>O molecules, the following will be observed in such a system. Because of the differences in pressure (concentration) of H<sub>2</sub>O molecules in different compartments, the transition of water molecules in the volume of their lower concentration, i.e. into the compartment of the salt solution, the volume of which is gradually increased, the solution is diluted, the pressure difference decreases, inhibiting further transport of H<sub>2</sub>O molecules. In equilibrium state levels in both parts of the cell will not change and the steady-stated hydrostatic pressure is defined as the osmotic pressure of the solution (Fig. 3.3.1.1, b) [9].

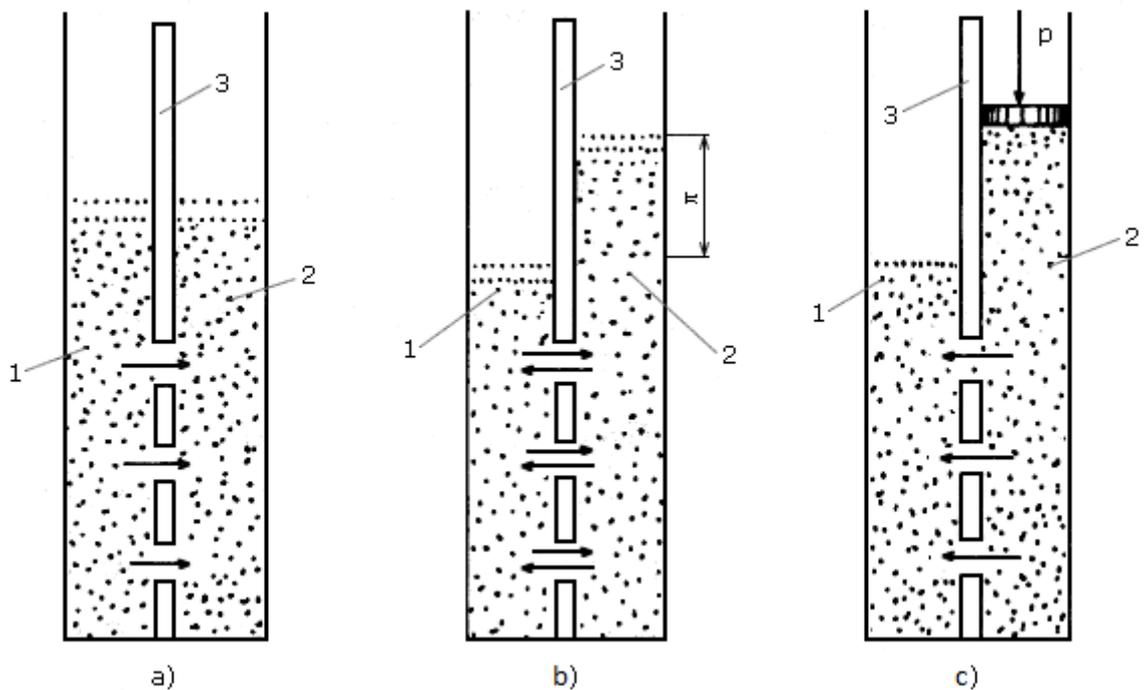


Figure 3.3.1.1 Schematic diagram of direct and reverse osmosis [9]:

a - the beginning of osmotic transfer; b - equilibrium state; c - reverse osmosis; 1 - fresh water; 2 - salt water; 3 - membrane; p - osmotic pressure of the solution.

If to apply external pressure that exceeds the osmotic pressure on the solution side, the rate of transition of water molecules from the solution through the semipermeable membrane will be greater than in the solution. This leads to obtaining of pure water in the compartment behind the membrane and to the high concentration of impurities in the solution to which the external pressure is applied (Fig. 3.3.1.1 (c)). The schematic diagram of the reverse osmosis process is shown in Fig. 3.3.1.2.

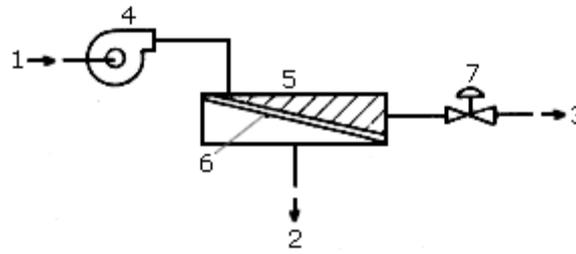


Figure 3.3.1.2. Schematic diagram of reverse osmosis installation [10]

1 - highly mineralized feed water; 2 - purified water; 3 - concentrate (waste water); 4 - high pressure pump; 5 - reverse osmosis module; 6 - semipermeable membrane; 7 - exhaust valve

Reverse osmosis and ultrafiltration are fundamentally different from the filtration processes, since during their operation precipitate does not form, as in filtering, but only two solutions with different concentrations of impurities form. However, to achieve a long service life of semipermeable membranes, a sufficiently complete purification of initial water from colloidal impurities and suspended solids is necessary.

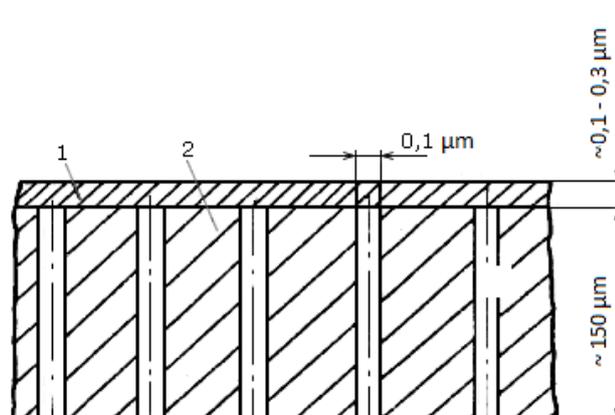


Figure 3.3.1.3 The structure of the semipermeable membrane [9]:

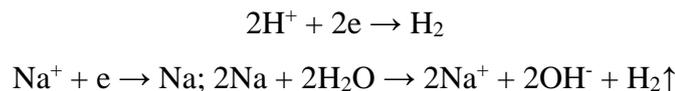
1 - active layer; 2 - supporting layer

The efficiency of reverse osmosis technology is determined by the properties of semipermeable membranes, which should be characterized by high separating ability (salinity) and the specific permeability, be chemically resistant and mechanically durable, have a low cost and sufficient (up to 5 years) service life without deterioration of operational characteristics. These requirements are met by polymer membranes made of cellulose acetate or aromatic polyamides. The latter are characterized by lower specific productivity, but are more resistant to chemical and biological factors, which ensures their greater durability. Reverse osmosis membranes have an asymmetric structure and consist of two layers (Fig. 3.3.1.3): the upper - active (thickness up to 0.30 microns) which is the separating part of the membrane itself, and the lower, coarse-grained (thickness of 100 - 200 microns) which is a substrate and provides mechanical strength of the membrane. Among the most important technological parameters of semipermeable membranes the following are used: permeability (specific capacity) and selectivity. The operating conditions of reverse osmosis units are determined by the coefficient of filtrate output. For ultrafiltration polyelectrolyte membranes are used, which are similar in structure to reverse osmosis membranes, but have a relatively larger pore diameter (more than 150 nm) [9].

### 3.3.2 Electrodialysis technology

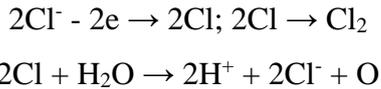
Electrodialysis is the process of removing ions of dissolved substances from solutions (conductors of the second kind) by transferring them through membranes in the field of direct electric current. It is known that when a constant electric field is applied to the solution, in the latter there is a movement of cations (including hydrogen ions) to the negative charged cathode, and anions to the anode. When ions come into contact with the corresponding electrodes, the following reactions occur [9]:

Cathodic reduction reactions:



and anodic oxidation reactions:





If the electrode cell made of cationite and passes only cations is placed near the cathode membrane, and near the anode - anionite, passes only anions, it will eliminate the transfer of  $\text{H}^+$  and  $\text{OH}^-$  ions formed at the electrodes and the cell volume will be divided into three chambers. In this case, in the cathode compartment of the medium can be only cations, moving toward the cathode and in the anode - only the anions moving to the anode. The concentration of ions in the middle chamber will decrease, i.e. the water will become less mineralized, and in the near-electrode chambers the mineralization will increase. The initial water supplied in the even-numbered camera (Fig. 3.3.2.1), loses ions impurities, i.e. desalted. In odd-numbered chambers water is enriched with salts. Demineralized water and concentrate are collected and separately removed from the apparatus.

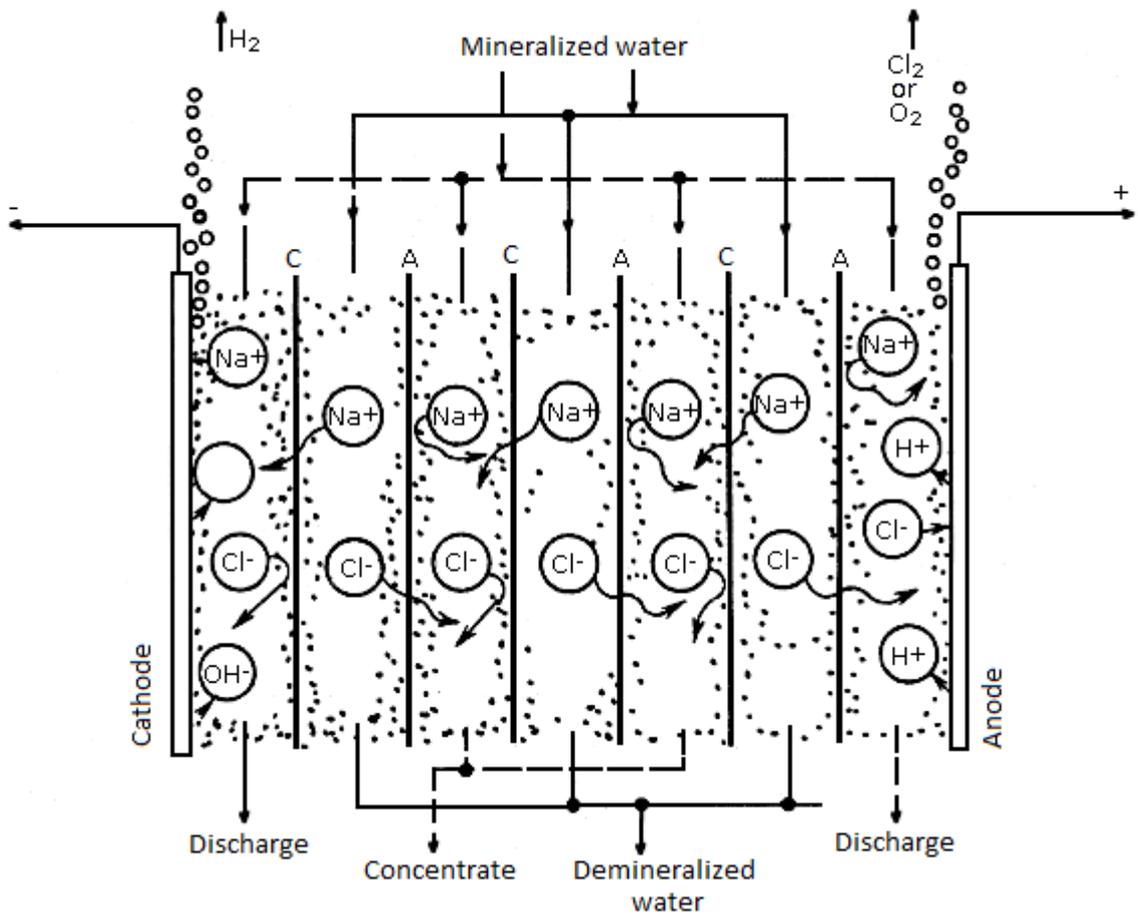


Figure 3.3.2.1 Scheme of multi-chamber electrolyszer [9]

C - cationic the membrane is permeable only to cations; And - anionic membrane is permeable only to anions;

Ionite membranes used in the electro dialysis process must have high selectivity, low permeability for water molecules, good electrical conductivity, high mechanical strength, chemical resistance, have a long service life in industrial conditions.

Serious obstacles to the deep desalination of water in electro dialysis technology are [9]:

- 1) increasing of electrical resistance in the cells with increasing degree of demineralization;
- 2) the water transfer through the membrane during osmosis;
- 3) decomposition of water because high electric current;
- 4) the possibility of precipitation on the membranes in the concentration chambers. It is shown experimentally that at the concentration of salts in desalination chambers below 200-300 mg/dm<sup>3</sup>, the energy consumption increases sharply, which limits the depth of water desalination to the specified limits.

Taking into account the noted limitations, the optimal level of salt content reduction of treated water in single-stage electro dialysis units does not exceed 40 – 50 %.

Construction of electro dialysis units is designed similar to filter press (Fig. 3.3.2.2) and included in the scheme of water treatment in series or in parallel, depending on the conditions of use. The alternation of desalting and concentrate chambers is provided by the framework-gaskets of dielectric (paronite, polyethylene, etc.) with a thickness of 0.7 - 1.0 mm. Channels for the supply and removal of the source water and concentrate are formed by holes stamped in the framework. Cameras placed inside the corrugated grid that distances membrane and also serves for turbulization of water flow. The initial water used in electro dialysis installations requires pre-processing in order to minimize the possibility of the formation of precipitation in the chambers of the suspended particles; subjected to electric coagulation of colloidal particles; sludge from the solid phase CaCO<sub>3</sub> and Mg(OH)<sub>2</sub>. In addition, ions of iron, manganese and organic substances should be removed from the water to concentrations of at least 50 µg/dm<sup>3</sup> for each, the presence of which leads to "poisoning" of the membranes, i.e. to reduce their electrical conductivity. [9]

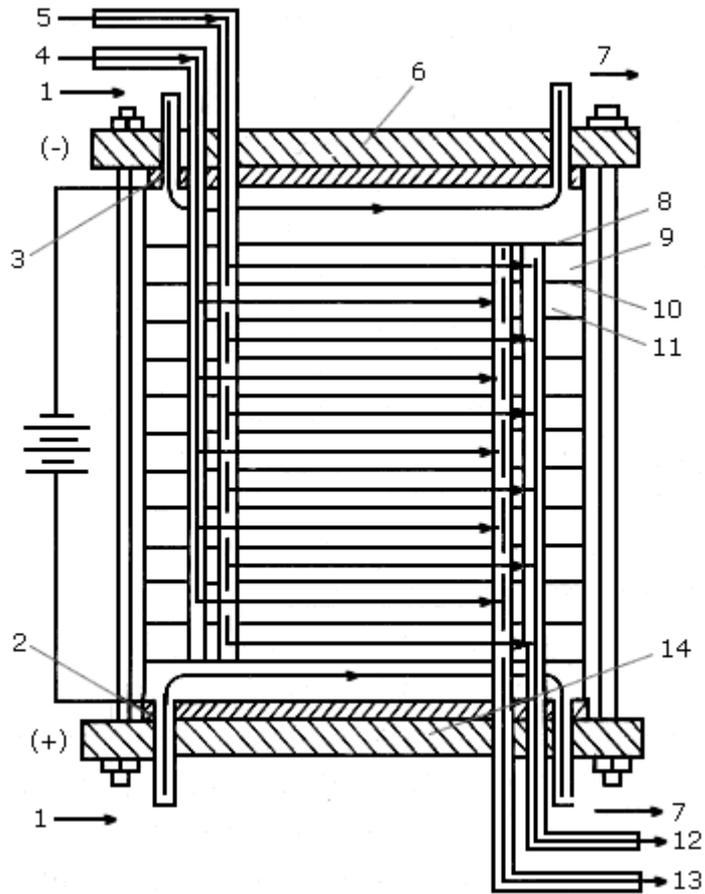
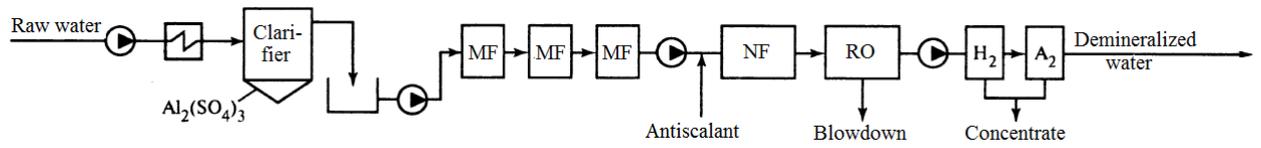


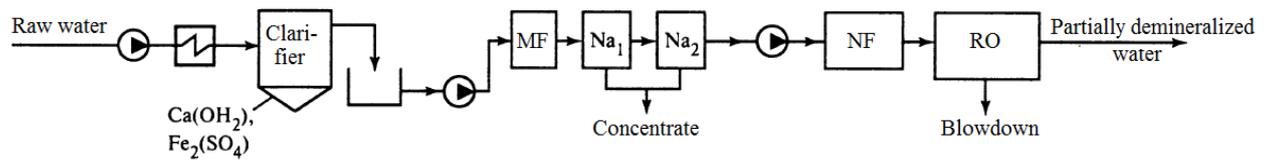
Figure 3.3.2.2 Scheme of multi-chamber electrodesalination apparatus [2]

1 - water for washing the electrode chamber; 2 - anode; 3 - cathode; 4 - water for washing concentrate chambers; 5 - supply of initial water to desalting chambers; 6 - upper pressure plate; 7 - drain from the electrode chamber; 8 - cationic membrane; 9 - gasket in the desalination chamber; 10 - anionite membrane; 11 - gasket in the condensate chamber; 12 - removal of treated water; 13 - removal of concentrate; 14 - lower plate

### 3.3.3 Samples of schemes of demineralization installations with RO [3]



MF — mechanical filter; NF — nanofiltration filter; RO — reverse osmosis unit; H<sub>2</sub> — H-cationic filter of the second stage; A<sub>2</sub> — anionite filter of the second stage.



MF — mechanical filter; NF — nanofiltration filter; RO — reverse osmosis unit; H<sub>2</sub> — H-cationic filter of the second stage; A<sub>2</sub> — anionite filter of the second stage; Na<sub>1</sub>, Na<sub>2</sub> — Na-cationic filters of the first and second stages.



United States» [7] were taken as initial raw water quality indicators. It contains thirteen indicators sets for different water sources in USA. So, it allows us to figure out real existing limits for each indicator. All values of indicators are arranged in ascending order with built-in function «Sort». Initial data is highlighted with yellow color.

## 4.2 Calculation of quality indicators by stages of water treatment

To select equipment for water treatment we should figure out how pure treated water should be. For this purpose, various standards exist. Such standards in Finland are developed and approved by Finnish Recovery Boiler Committee. So, below, table 4.2 represents main values of water quality indicators for recovery boilers installable at paper mills. [10] These requirements variation depends on operating physical parameters of the boiler (pressure).

Table 4.2 Boiler water quality according standards

Indicators	8,5 MPa	11 MPa	16 MPa
Na <sup>+</sup> , mEq/L	0,196	0,152	0,109
Ca <sup>2+</sup> , mEq/L			
Mg <sup>2+</sup> , mEq/L			
TH, mEq/L			
HCO <sub>3</sub> <sup>-</sup> , mEq/L			
Cl <sup>-</sup> , mEq/L	0,017	0,011	0,006
SO <sub>4</sub> <sup>2-</sup> , mEq/L	0,025	0,017	0,008
SiO <sub>2</sub> , mg/L	0,900	0,400	0,100
CO <sub>2</sub> , mg/L			
CO <sub>3</sub> <sup>2-</sup> , mEq/L			
Fe, mg/L	0,005	0,005	0,005
TSS, mg/L			
Oxidability, mgO <sub>2</sub> /L			
pH	9,5-9,8	9,4-9,7	9,4-9,6

So the purpose of next steps is to calculate and design the scheme of water treatment stage by stage which will satisfy this standard. And then, select appropriate equipment and its energy consumption.

There are some necessary stages of water treatment: pre-treatment – in the beginning (sedimentation process and mechanical filters), first and second stages of ion-exchange filters and the final, third «after-treatment» stage (mixed-bed filters). See chapters 2, 3, for details. As the most popular, ion-exchange technology was taken for analysis.

#### **4.2.1 Water clarification**

Depends on raw water impurities composition, various methods of sedimentation applied. Because of huge amount of water that needs to be treated and usually high level of turbidity, the process is carried out with chemicals feed. Electrocoagulation is less suitable and is not considered in this analysis. The calculation process is fully automated and the choice of clarification method is made in accordance with algorithm displayed in flowchart below.

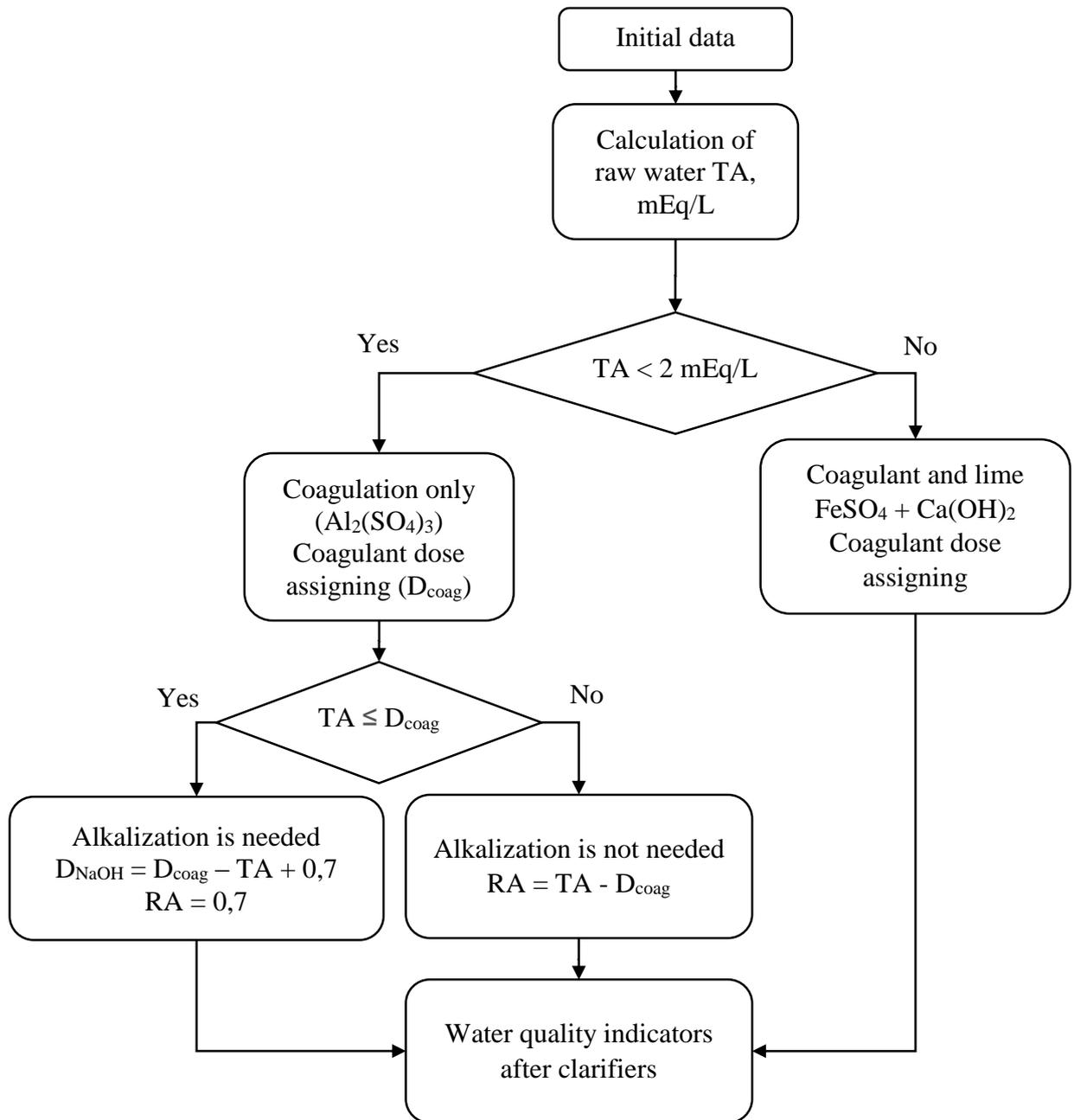


Figure 4.2.1 Algorithm of sedimentation method selection

So, here we have two options: coagulation with  $\text{Al}_2(\text{SO}_4)_3$  when total alkalinity of raw water is less than 2 mEq/L and process of coagulation with lime adding, where  $\text{FeSO}_4$  is used as coagulant. Methods of calculations of water quality indicators after both of these processes are typical and were performed according dedicated pre-treatment calculations literature. [2, 9] More detailed processes are considered in chapter 2.

Mechanical filters are located after clarifiers in the water treatment scheme and their only function is to reduce concentration of total suspended solids in clarified water. TSS after MF usually does not exceed 1 mg/L.

#### **4.2.2 Water quality indicators calculation by stages of ion-exchange technology**

Deeper explanation of each stage process is represented in the chapter 3. Only real outcomes affecting on calculation process are considered here.

As it was said previously, each ion-exchange filter works until breakthrough of indicating ion (till concentration of ion, which had to be taken, begins rise). In that moment filter starts regeneration. Till that moment water quality indicators stay the same and their changes represented stage by stage below.

##### *1st stage of H-cation exchange*

Here cations are removed, concentrations:  $\text{Ca}^{2+} = 0$ ,  $\text{Mg}^{2+} = 0.02$  mEq/L,  $\text{Na}^+ = 0.1$  mEq/L

The medium is acidic,  $\text{pH} < 7$

TSS and oxidability are fully removed.

##### *1st stage of OH-cation exchange*

Here anions are removed, concentrations:  $\text{SO}_4^{2-} = 0$ ,  $\text{Cl}^- = 0.03$  mEq/L

The medium is still acidic,  $\text{pH} < 7$

##### *Degasser*

Here the main amount of dissolved carbon dioxide is removed:  $\text{CO}_2 = 4$  mg/L

##### *2nd stage of H-cation exchange*

Here residual cations are removed, concentrations:  $\text{Mg}^{2+} = 0$ ,  $\text{Na}^+ = 0.01$  mEq/L

##### *2nd stage of OH-cation exchange*

Here residual anions, dissolved silicic and carbon acids are removed, concentrations:

$\text{Cl}^- = 0.03$  mEq/L,  $\text{SiO}_2 = 0.05$  mg/L,  $\text{CO}_2 = 0$

### Mixed-bed units

Here all residual ions are removed:  $\text{Cl}^- = 0$ ,  $\text{SiO}_2 = 0$ ,  $\text{Na}^+ = 0.005 \text{ mEq/L}$

All other indicators are known, calculable or stay the same. The final result is a table of indicators values through all stages of water treatment. And it can be compared with required boiler water quality to figure out how well demineralized the final water should be. Tables are displayed in figure 4.2.2.

Indicators	Raw water	Coag.	M	H1	OH1	D	H2	OH2	Mixed-bed		8,5 MPa	11 MPa	16 MPa
$\text{Na}^+$ , mEq/L	0,087	1,238	1,238	0,100	0,100	0,100	0,010	0,010	0,005		0,196	0,152	0,109
$\text{Ca}^{2+}$ , mEq/L	0,085	0,085	0,085	0,000	0,000	0,000	0,000	0,000	0,000				
$\text{Mg}^{2+}$ , mEq/L	0,033	0,033	0,033	0,020	0,020	0,020	0,000	0,000	0,000				
TH, mEq/L	0,118	0,118	0,118	0,020	0,020	0,020	0,000	0,000	0,000				
$\text{HCO}_3^-$ , mEq/L	0,049	0,700	0,700	0,000	0,000	0,000	0,000	0,000	0,000				
$\text{Cl}^-$ , mEq/L	0,073	0,139	0,139	0,139	0,030	0,030	0,030	0,030	0,000		0,017	0,011	0,006
$\text{SO}_4^{2-}$ , mEq/L	0,017	0,517	0,517	0,517	0,000	0,000	0,000	0,000	0,000		0,025	0,017	0,008
$\text{SiO}_2$ , mg/L	0,400	0,200	0,200	0,200	0,200	0,200	0,200	0,050	0,000		0,900	0,400	0,100
$\text{CO}_2$ , mg/L	13,873	0,000	0,000	0,033	0,033	4,000	4,000	0,000	0,000				
$\text{CO}_3^{2-}$ , mEq/L	0,000	0,001	0,001	0,000	0,000	0,000	0,000	0,000	0,000				
Fe, mg/L	0,000	0,150	0,150	0,020	0,020	0,020	0,000	0,000	0,000		0,005	0,005	0,005
TSS, mg/L	0,000	10,000	1,000	0,000	0,000	0,000	0,000	0,000	0,000				
Oxidability, $\text{mgO}_2/\text{L}$	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000				
pH	5,800	7,000	7,000	3,183	4,523	4,523	7,000	7,000	7,000		9,5-9,8	9,4-9,7	9,4-9,6

Figure 4.2.2 Changes in water quality through the stages of treatment and boiler water quality according standards

### 4.3 Calculation of ion-exchange technology

This part of calculations is needed to quantify the flow rate of reagents, intern water needs and to select filters and their number. The calculation of the water treatment scheme begins with the equipment installed in the tail of the scheme (in this case with mixed-bed filter), in order to take into account, the additional load on the previous filters of water used for their own needs. Methods of calculation and formulas for each parameter are shown below.

Table 4.3 Calculations guidelines

1. Rated capacity, m <sup>3</sup> /h	$Q_{st} = Q_{pr} + Q_{pr}^{in}$ , where $Q_{pr}$ – rated capacity of the previous stage, m <sup>3</sup> /h, $Q_{pr}^{in}$ - hourly consumption for internal needs of previous stage, m <sup>3</sup> /h
2. Number of filters in operation	(n) This is initial variable for further iterations. Always 1 filter is added to this number as a spare.
3. Capacity of the one filter, m <sup>3</sup> /h	$Q_f = Q_{st}/n$
4. Filtration rate, m/h	(w) Can be changed a little as additional variable for iterations. Usually equals to 40 for mixed-bed and H2 filters
5. Required cross-sectional area of filters, m <sup>2</sup>	$F = Q_{st}/n$
6. Cross-section of the one filter, m <sup>2</sup>	$f = F/n$
7. Diameter, m	$d = \sqrt{f * 4/\pi}$
8. Diameter of standard filter, m	(D) Is taken from the row of standard filters diameters close to found diameter.
9. Standard filter	Is chosen with standard diameter.
10. Cross-section area of standard filter, m <sup>2</sup>	$A = \pi * D^2/4$
11. Height of the ion exchanger layer of standard filter, m	(h <sub>1</sub> ) Is chosen with standard filter.
12. Actual filtration rate, m/h	$w_a = Q_{st}/(f * n)$
13. Type of filtrating material	Name of the resin
14. Ion-exchange capacity, Eq/m <sup>3</sup>	(E) Is chosen with resin.
15. Duration of filter cycle, h	$T = f * h_1 * E * n / (Q_{st} * C)$ , where C – concentration of the removable impurity.
16. Daily number of filters regenerations, 1/day	$m = 24 * n / T$
17. Reagent	Name of the reagent.

18. Specific reagent consumption, kg/m <sup>3</sup>	(b) Is chosen with reagent.
19. 100%-reagent consumption for one regeneration, kg	$s^{100} = f \cdot h_1 \cdot b$ It is not calculated for MF
20. 100%-reagent daily consumption, kg/day	$s_d^{100} = s^{100} \cdot m$ It is not calculated for MF
21. Water consumption for a mixture separation, m <sup>3</sup> /reg	$v_{m.s} = w_s \cdot f \cdot (t_s/60)$ , where $w_s$ – separation speed, $t_s$ – separation time. Calculated for mix-bed filters only.
22. Water consumption for the establishment of counter-flows, m <sup>3</sup> /reg	$v_{cc} = 2 \cdot w_{cc} \cdot f \cdot (t_{cc}/60)$ , where $w_{cc}$ – establishing rate, $t_{cc}$ – establishing time. Calculated for mix-bed filters only.
23. Specific water consumption for loosening, L/(cm <sup>2</sup> *s)	(i) It depends on filter type.
24. Duration of filter loosening, min	(ti) Constant and equals 20 min.
25. Loosening water consumption, m <sup>3</sup> /reg	$v_1 = f \cdot i \cdot t_l \cdot 60 / 10^3$
26. Concentration of regenerating solution, %	(C <sub>r</sub> ) It depends.
27. Water consumption for solution preparation, m <sup>3</sup> /reg	$v_{s.pr} = s^{100} \cdot 100 / (C_r \cdot 10^3)$ It is not calculated for MF
28. Specific water consumption for rinsing, m <sup>3</sup> /m <sup>3</sup>	(a) It depends on filter type.
29. Water consumption for rinsing, m <sup>3</sup> /reg	$v_r = f \cdot h_1 \cdot a$
30. Final rinse water consumption, m <sup>3</sup> /reg	$v_f = 5 \cdot A \cdot h_1$ It is not calculated for MF
31. Total water consumption for regeneration, m <sup>3</sup> /reg	$v_{tot} = v_1 + v_{s.pr} + v_r$
32. Hourly consumption for internal needs, m <sup>3</sup> /h	$Q_{pr}^{in} = v_{tot} \cdot m / 24$
33. Rinsing rate, m/h	(w <sub>rs</sub> ) It depends on filter type.
34. Time of passage of the regeneration solution, min	$t_{rs} = v_{s.pr} \cdot 60 / (f \cdot w_{rs})$ It is not calculated for MF
35. Rinsing duration, min	$t_r = v_r \cdot 60 / (f \cdot w_{rs})$
36. Total regeneration time, min	$t_{tot} = t_l + t_{rs} + t_r$

## 4.4 Water treatment equipment selection

As it was said in previous chapters the main goal of all calculations is to figure out how raw water quality indicators impact on energy consumption of water treatment through equipment. For based on ion-exchange technology water treatment, auxiliary equipment acts as energy consumers. So, air blowers for degassers and pumps of the main treatment process are considered in this analysis as energy consumers.

This part of calculations is fully automated, consequently there is an algorithm that allows to select equipment and it is displayed in the flowchart below. (fig. 4.4.1)

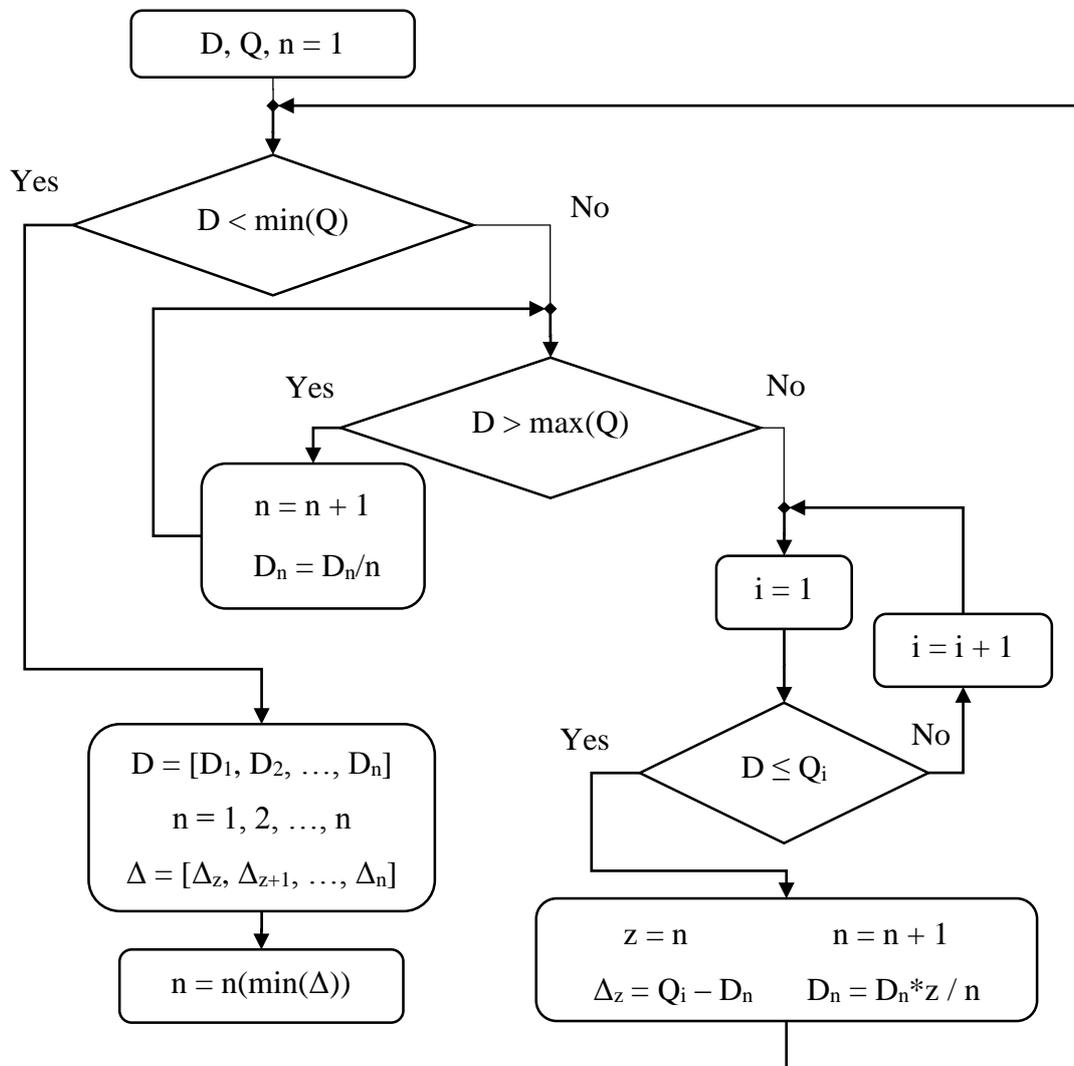


Figure 4.4.1 Algorithm of selection of number of pumps.

Here, D – required capacity of the pump, Q – row of standard capacities for certain type of the pump, n – number of pumps.

Microsoft Excel sheets are not programming environment, so implementation of this algorithm with Excel built-in functions looks a bit different from code sequence but works the same way. This algorithm gives opportunity to choose the best possible number of pumps in terms of required capacity.

This is performed for every kind of pumps and for degassers blowers. Only calculation of initial required capacity differs. The same algorithm is implemented for tanks selection, except that instead of capacities tanks volumes are used.

After the number of pumps and capacity of the one pump is defined the appropriate standard pump with known power of electric engine is taken. With simple calculations we can find annual energy consumption both for each group of pumps as well as the total energy consumption. Results of such calculations for one of the initial data sets are shown in table 4.4.1.

Table 4.4.1 Energy consumption

Pump	Name	Number of pumps	Power of one pump, kW	Pumps power, kW	Energy consumption, kW*h/a
Standart degasser blower	БЦ-6-28 №5	1	7,50	7,5	65700
Coagulant dosing pumps	НД-400/10	1	1,10	1,10	9636
Lime dosing pumps	НД-1600/10	8	3,00	24,00	210240
Acid dosing pumps	НД-630/10	1	1,10	1,10	9636
Caustic dosing pumps	НД-630/10	3	1,10	3,30	28908
Pumps of clarified water	К-90/35	5	15,00	75,00	657000
Pumps of degassed water	К-90/35	3	15,00	45,00	394200
Pumps of mechanical filters	К-20/18	1	2,20	2,20	19272
Pumps of mechanical filters rinse water reuse	К-20/18	2	2,20	4,40	38544
Pumps of ion-exchange filters internal needs of 1st stage	К-20/18	1	2,20	2,20	19272
Pumps of ion-exchange filters internal needs of 2nd and 3d stages	К-8/18	1	1,50	1,50	13140
Recirculation pumps of coagulant	Х-3/40	2	4,00	8,00	70080
Recirculation pumps of lime	Х-20/31	4	5,50	22,00	192720
Sludge water pumps	СД-32/40	1	11,00	11,00	96360
				<b>Power of water treatment, kW</b>	<b>Total energy consumption, kW*h/a</b>
				208,3	1824708

## **5. DATA ANALYSIS**

An example of final result shown in the chapter 4 is energy consumption for set of auxiliary equipment of water treatment. This result will change for every set of initial data. Consequently, changing initial data in some way we can identify dependence of the energy consumption from water quality indicators. In this chapter the analysis and conclusions are considered.

### **5.1 Data saving**

From the figure 4.1 it can be seen that there are 12 water quality indicators which can be changed in pretty wide range. In addition, the final result will be affected by water treatment capacity and temperature of raw water. For further analysis, assume that capacity and temperature are constant because we suppose that boiler water demand is constant and temperature of raw water is maintained with water heaters at the pre-treatment inlet. Nevertheless, even if we guess that the water indicators are only variables affecting the final result, there is plenty of combinations of initial data to be analyzed. Because of this I made the simple code which allows to save obtained results. It works as follows: after every change of one of the indicators all sheets recalculate and energy consumptions save in the next free column on the sheet. For illustration, the process is shown in the figure 5.1.1.

	A	B	C	D	E	F	G	H
1								
2	<b>1</b>						Silica, mg/L	
3						Current data	0,4	
4		Silica, mg/L	0,4		Standart degasser blower, kW*h/a	65700	65700	
5		Iron, mg/L	8,4		Coagulant dosing pumps, kW*h/a	9636	9636	
6		Calcium, mg/L	9,6		Lime dosing pumps, kW*h/a	9636	9636	
7		Magnesium, mg/L	12,0		Acid dosing pumps, kW*h/a	9636	9636	
8		Sodium and Potassium, mg/L	13,0		Caustic dosing pumps, kW*h/a	28908	28908	
9		Bicarbonate, mg/L	16,0		Pumps of clarified water, kW*h/a	262800	262800	
10		Sulfate, mg/L	23,0	0,80	Pumps of degassed water, kW*h/a	394200	394200	
11		Chloride, mg/L	34,0	2,60	Pumps of mechanical filters loosening, kW*h/a	19272	19272	
12		Nitrate, mg/L	39,0	0,00	Pumps of mechanical filters rinse water reuse, kW*h/a	38544	38544	
13		TSS, mg/L		0,00	Pumps of ion-exchange filters internal needs of 1st stage, kW*h/a	13140	13140	
14		Oxidability, mgO <sub>2</sub> /L		0,00	Pumps of ion-exchange filters internal needs of 2nd and 3d stages, kW*h/a	13140	13140	
15		pH		5,8	Recirculation pumps of coagulant, kW*h/a	70080	70080	
16					Recirculation pumps of lime, kW*h/a	70080	70080	
17					Sludge water pumps, kW*h/a	48180	48180	
18								
19								
20					Total, kW*h/a	1052952	1052952	
21								

	A	B	C	D	E	F	G	H
1								
2	<b>2</b>						Silica, mg/L	Silica, mg/L
3						Current data	0,4	39
4		Silica, mg/L	39		Standart degasser blower, kW*h/a	65700	65700	65700
5		Iron, mg/L	0,00		Coagulant dosing pumps, kW*h/a	9636	9636	9636
6		Calcium, mg/L	1,70		Lime dosing pumps, kW*h/a	9636	9636	9636
7		Magnesium, mg/L	0,40		Acid dosing pumps, kW*h/a	9636	9636	9636
8		Sodium and Potassium, mg/L	2,00		Caustic dosing pumps, kW*h/a	28908	28908	28908
9		Bicarbonate, mg/L	3,00		Pumps of clarified water, kW*h/a	262800	262800	262800
10		Sulfate, mg/L	0,80		Pumps of degassed water, kW*h/a	394200	394200	394200
11		Chloride, mg/L	2,60		Pumps of mechanical filters loosening, kW*h/a	38544	19272	38544
12		Nitrate, mg/L	0,00		Pumps of mechanical filters rinse water reuse, kW*h/a	38544	38544	38544
13		TSS, mg/L	0,00		Pumps of ion-exchange filters internal needs of 1st stage, kW*h/a	13140	13140	13140
14		Oxidability, mgO <sub>2</sub> /L	0,00		Pumps of ion-exchange filters internal needs of 2nd and 3d stages, kW*h/a	13140	13140	13140
15		pH	5,8		Recirculation pumps of coagulant, kW*h/a	70080	70080	70080
16					Recirculation pumps of lime, kW*h/a	70080	70080	70080
17					Sludge water pumps, kW*h/a	48180	48180	48180
18								
19								
20					Total, kW*h/a	1072224	1052952	1072224
21								19272

Figure 5.1.1 Illustration of automatic data saving process

The code that makes it run properly is shown in the figure 5.1.2. The code trigger is related to event of data changing in the cells C4:C15 where indicators are. Then, it seeks for a last column for rows of these cells and fills them with data of energy consumption obtained with all the sheets recalculation. Variable «z» in the code is responsible for determining of the changed cell and through this it becomes possible to add to the filled data the name of the changed parameter and its value. The final part of the code is needed to make all this looks good on the sheet.

```

Private Sub Worksheet_Change(ByVal Target As Range)
Dim KeyCells As Range

'The variable KeyCells contains the cells that will cause an alert when they are changed.

Set KeyCells = Range("C4:C15")
If Not Application.Intersect(KeyCells, Range(Target.Address)) _
Is Nothing Then

Dim wS As Worksheet, LastCol As Long, x As Long, z As Long

Set wS = ThisWorkbook.Worksheets("Analytics")
Set ECwS = ThisWorkbook.Worksheets("Energy consumption")

'Seeking for last column and adding of a new value

LastCol = wS.Cells(4, wS.Columns.Count).End(xlToLeft).Select
x = ActiveCell.Column

z = Str(Target.Rows(1).Row) 'Number of changed cell

Cells(2, x + 1) = wS.Cells(z, 2)
Cells(2, x + 1).Columns.AutoFit
Cells(3, x + 1) = wS.Cells(z, 3)

Cells(4, x + 1) = ECwS.Cells(4, 7)
Cells(5, x + 1) = ECwS.Cells(5, 7)
Cells(6, x + 1) = ECwS.Cells(6, 7)
Cells(7, x + 1) = ECwS.Cells(7, 7)
Cells(8, x + 1) = ECwS.Cells(8, 7)
Cells(9, x + 1) = ECwS.Cells(9, 7)
Cells(10, x + 1) = ECwS.Cells(10, 7)
Cells(11, x + 1) = ECwS.Cells(11, 7)
Cells(12, x + 1) = ECwS.Cells(12, 7)
Cells(13, x + 1) = ECwS.Cells(13, 7)
Cells(14, x + 1) = ECwS.Cells(14, 7)
Cells(15, x + 1) = ECwS.Cells(15, 7)
Cells(16, x + 1) = ECwS.Cells(16, 7)
Cells(17, x + 1) = ECwS.Cells(17, 7)

'Format painting

ActiveCell.Range("A1:A14").Select
Selection.Copy
ActiveCell.Offset(0, 1).Range("A1:A14").Select
Selection.PasteSpecial Paste:=xlPasteFormats, Operation:=xlNone, _
SkipBlanks:=False, Transpose:=False
Application.CutCopyMode = False

End If
End Sub

```

Figure 5.1.2 Code of the automatic data saving process

## **5.2 Arranging and structuring of obtained data**

The analyzing of the data is alternately change each of the parameters. Because indicators are not independent and depend on each other in many different ways throughout calculation, enumeration of values for each indicator will be made with others indicators limit values (minimum and maximum). Departure point of analyzing process is detection of water quality indicators affecting energy consumption. Thus, minimum and maximum value of each parameter were taken to see the difference in energy consumption, if there is no one, then this parameter doesn't affect significantly enough and can be skipped.

So, as a result only 7 indicators influence the choice of equipment and its power: calcium, magnesium, sodium and potassium, bicarbonate, sulfate, chloride and in addition to concentrations, pH changes have significant impact. The tables with highlighted names of indicators can be seen at "Analytics" sheet in attached Excel calculations.

Graphs below define sequence of total energy consumption from initial values of changed water quality indicator. First «MAX» graph represents changes in demand with maximum values of all other indicators of raw water. This graph is intended to show how much this certain indicator has affected on final result when concentrations of other impurities are maximized. The second «MIN» one, instead, showing how consumption behaves when initial water is originally pretty clean and how certain impurity separately from others influences choice of equipment.

### 5.2.1 Calcium

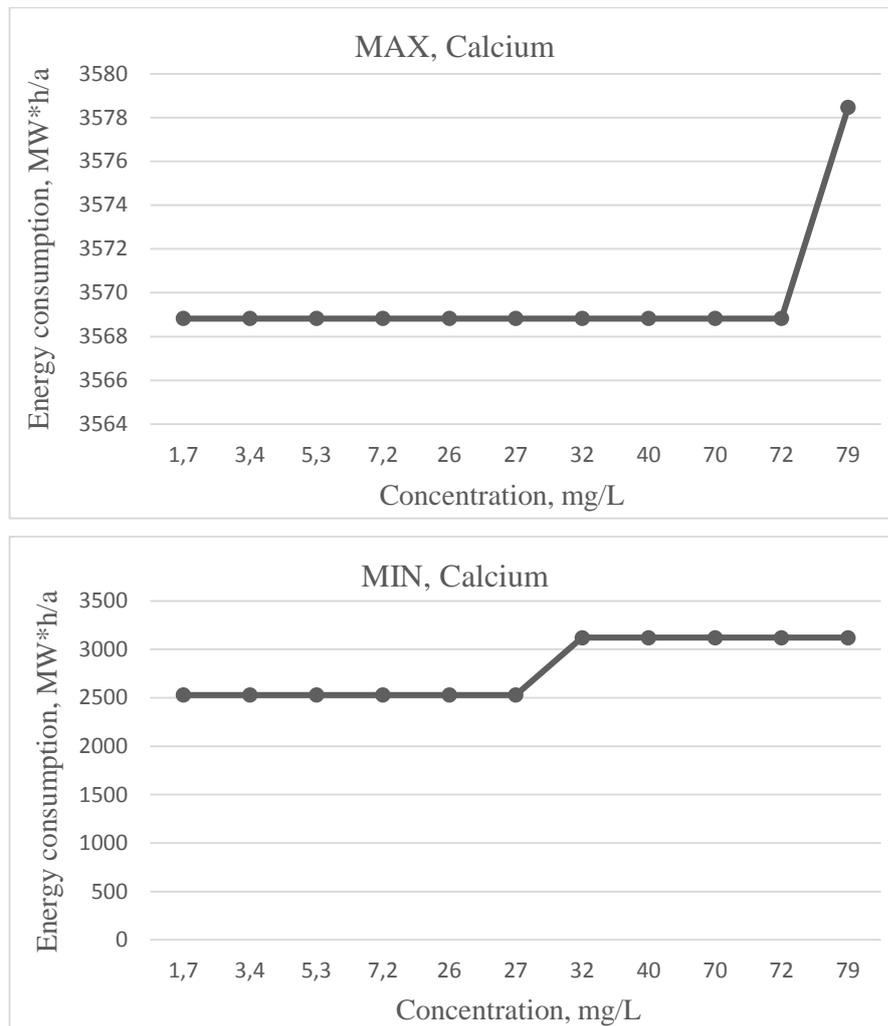


Figure 5.2.1 Energy consumptions as a function of calcium concentration in raw water

To analyze these pictures in proper way we need to consider some facts. It can be seen that increase of the consumption on the second graph is much bigger. And from the tables can be seen that in first case the increase is obtained with coagulant dosing pumps and that the second case increase is a result of changed demand of clarified water pumps. So, we can say that rise of calcium concentration affects most of all water pre-treatment.

## 5.2.2 Magnesium

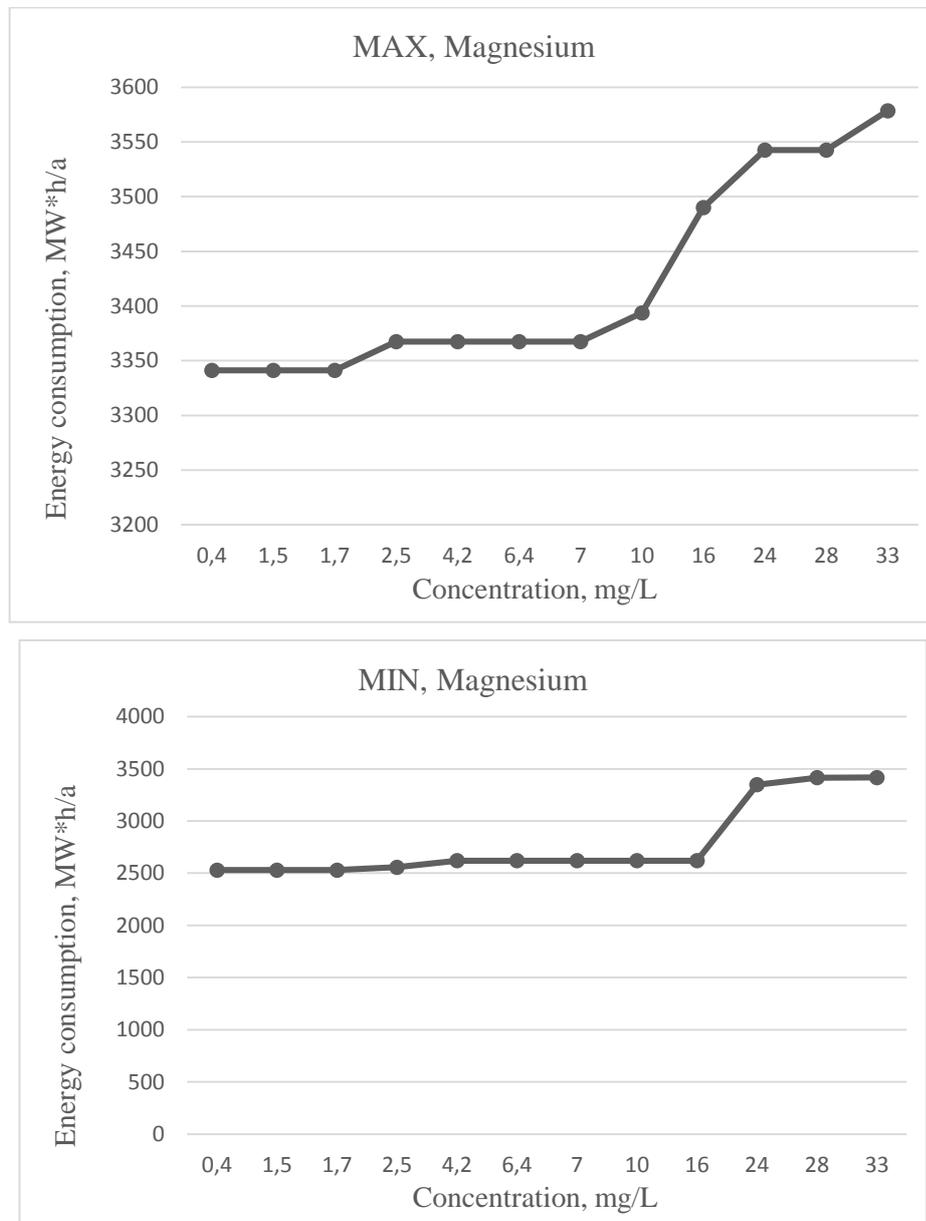


Figure 5.2.2 Energy consumptions as a function of magnesium concentration in raw water

Here the constant increase can be seen on the first graph. The dose of lime is a function of magnesium concentration and the constant elevation of concentration leads to constant rise of dose of lime and then to rise of energy demand of lime dosing pumps. For «MIN» option, there is quite stable rise of demand of recirculation pumps of lime in addition to dosing pumps.

### 5.2.3 Sodium and potassium

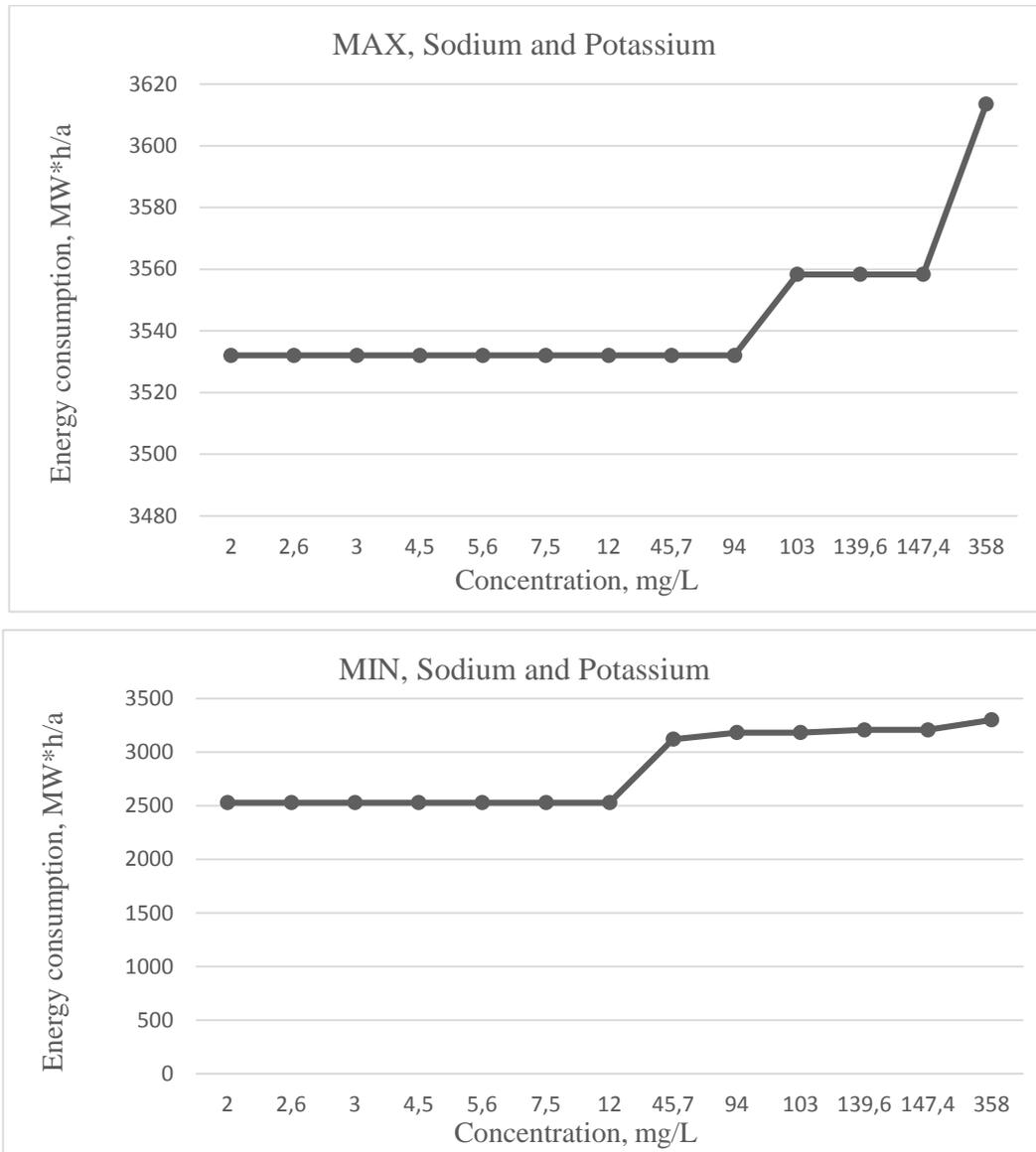


Figure 5.2.3 Energy consumptions as a function of sodium and potassium concentration in raw water

Again, the moderate increase can be seen in the first graph and more significant on the second one. Energy consumption contains demand of coagulant and lime dosing pumps and recirculation pumps of coagulant for first case and for second to these three kinds of pumps sludge and clarified water pumps join. All these pump groups are related to water pre-treatment.

### 5.2.4 Bicarbonate

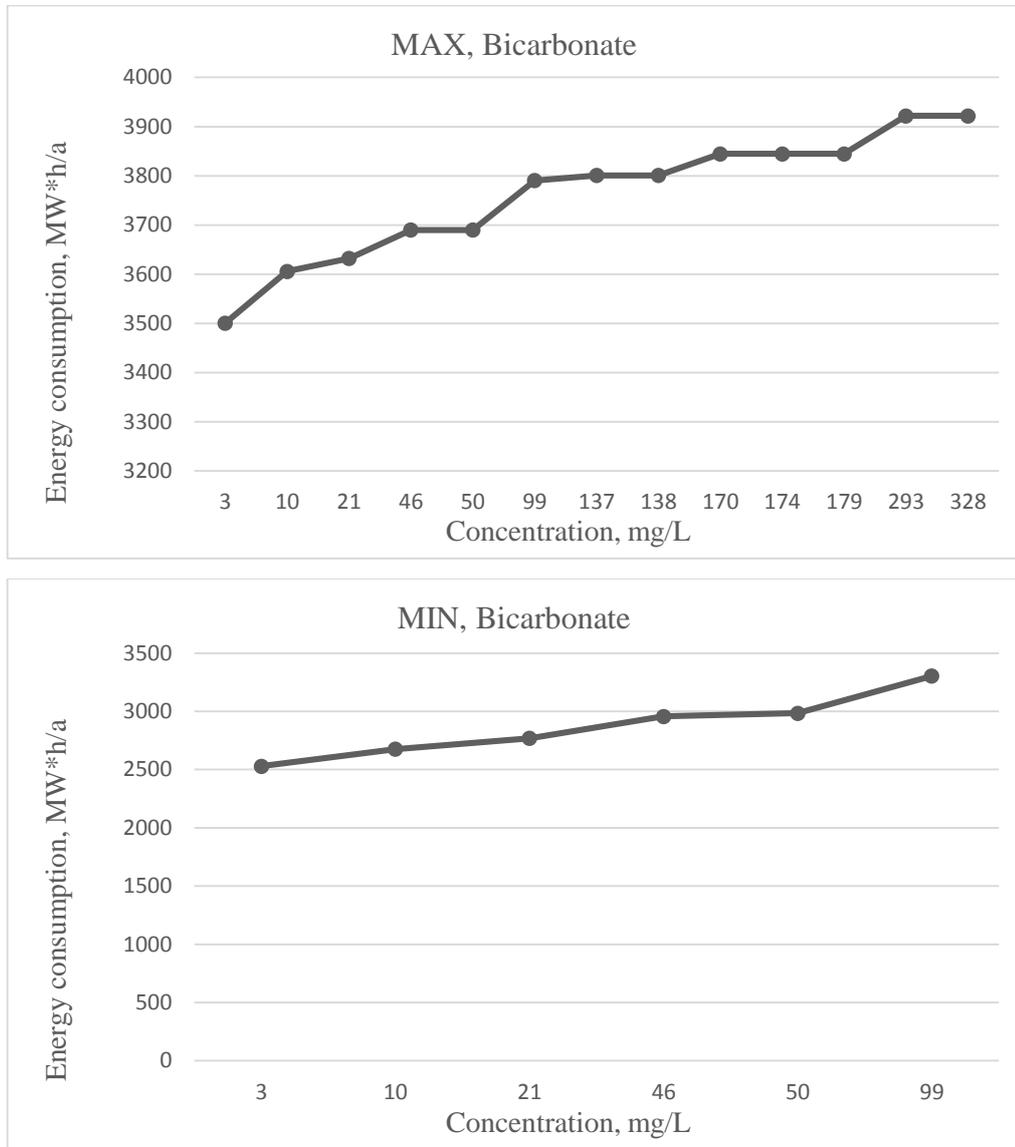


Figure 5.2.4 Energy consumptions as a function of bicarbonate concentration in raw water

Here the picture of change is pretty the same. Changes of consumption are related to pre-treatment intern energy demand. Reagents dosing pumps, recirculating and sludge pumps constitute «MAX» changes. «MIN» has constant grow affected with lime dosing and recirculating pumps only.

### 5.2.5 Sulfate

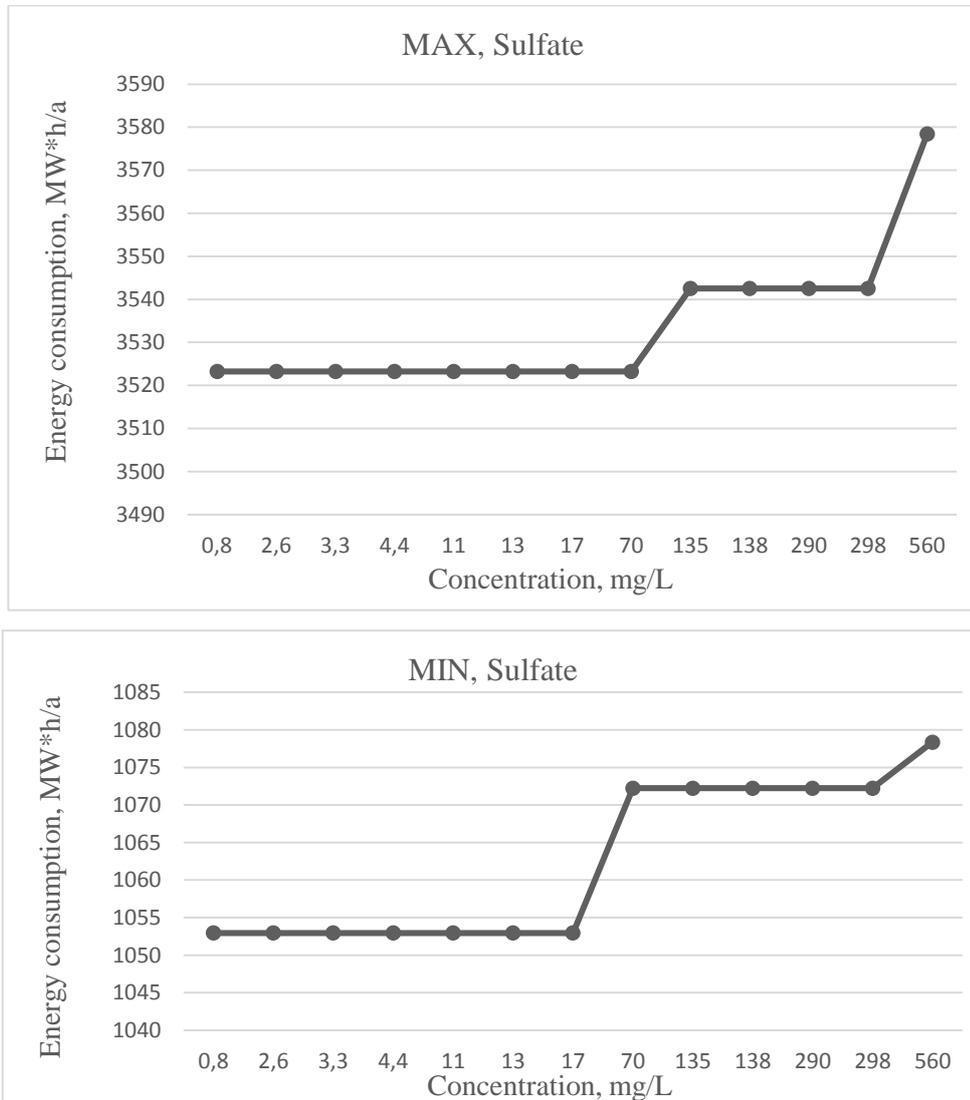


Figure 5.2.5 Energy consumptions as a function of sulfate concentration in raw water

Here, in addition to energy consumption of dosing pumps, noticeable contribution pumps of mechanical filters loosening, reuse water and ion-exchange filters make. But in fact impact is not great.

## 5.2.6 Chloride

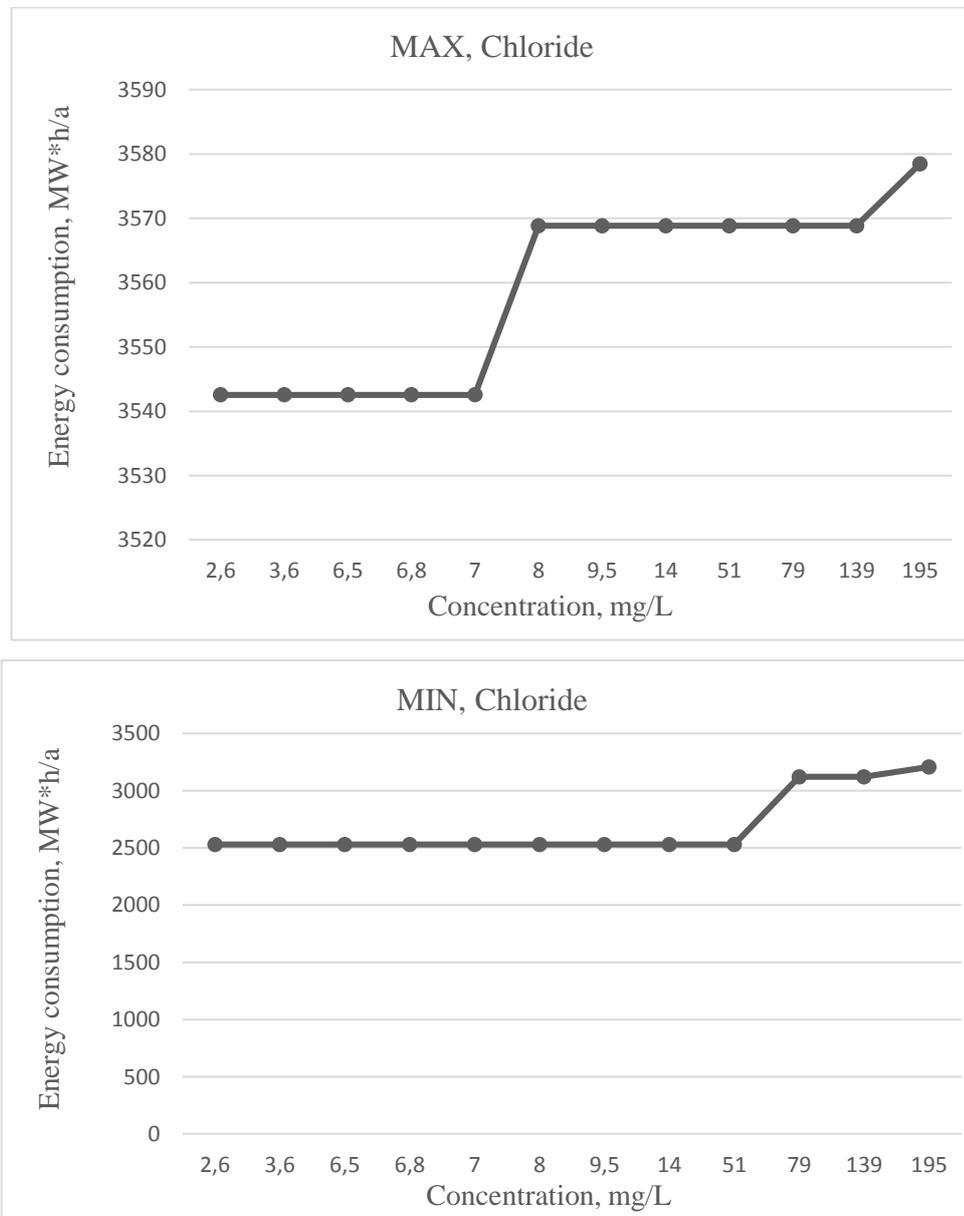


Figure 5.2.6 Energy consumptions as a function of chloride concentration in raw water

Here, again the main energy consumption is taken by pumps related to pre-treatment. For high concentrations impact is not too big. In that time, for low concentrations consumption clarified water pumps contribute significant in rise of consumption.

## 5.2.7 pH

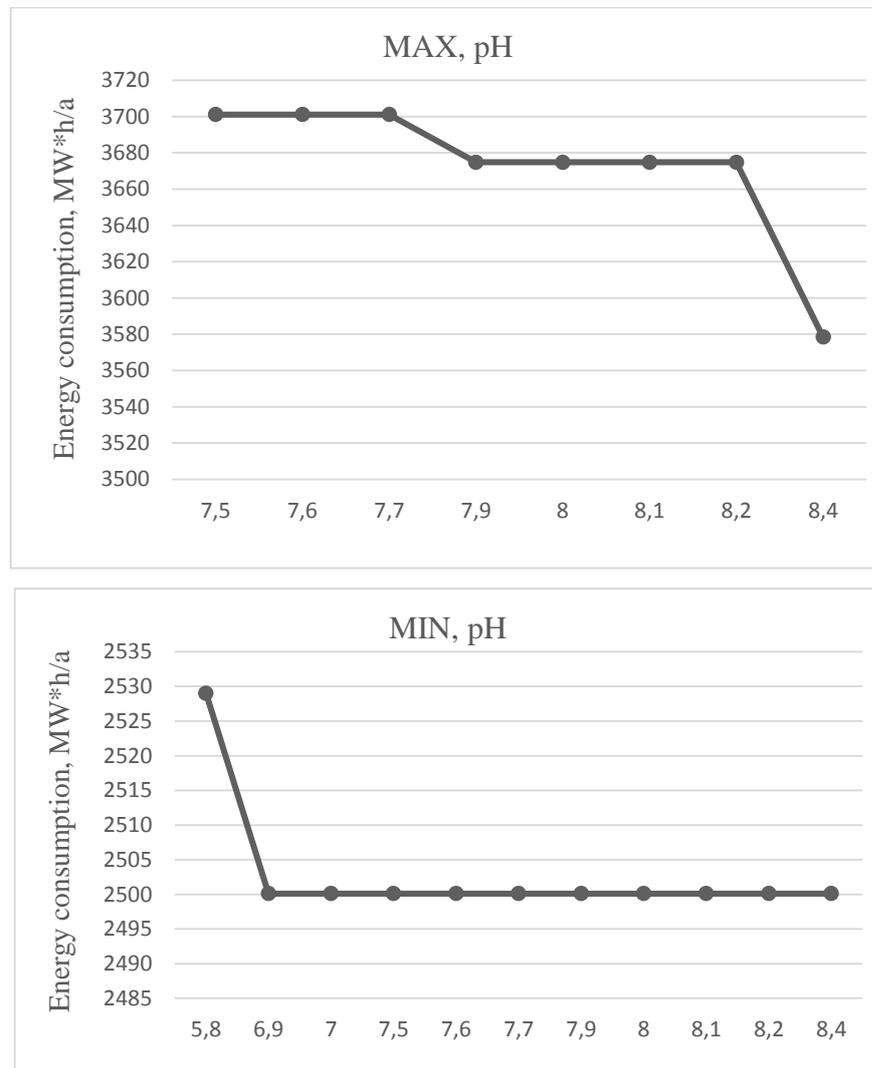


Figure 5.2.7 Energy consumptions as a function of pH

Here an interesting picture can be seen, in both cases the function is decreasing. As it can be seen from the tables of data pumps, leading to changes are lime dosing and recirculating pumps. Sequence is pretty simple: fractions of carbo till pH is equal to 8.3 are carbonic acid and lower amount of bicarbonate ion. When we rise pH value,  $\text{CO}_2$  converts to  $\text{HCO}_3^-$  ions. Because dose of lime is a function of carbonic acid consisted in raw water, dose of lime decrease and then required capacity of lime dosing and recirculating pumps declines and it leads to decrease of the energy consumption shown in figure 5.2.7.

## 6. CONCLUSIONS

Here I would like to show outcome of analysis. I would like to consider all indicators contributions, compare them and show which pumps contributed more than others affecting the final numbers. First of all, the total difference between minimum and maximum values of indicators will show in what circumstances water treatment consumes most of all and in which least.

### 6.1 Indicators

Table 6.1 Difference between minimal and maximal value of each indicator

<b>Increment of total EC</b>	<b>kW*h/a</b>
MIN, Magnesium	887388,00
MIN, Bicarbonate	774384,00
MIN, Chloride	678024,00
MIN, Calcium	591300,00
MIN, Sodium and Potassium	490560,00
MIN, Sulfate	471288,00
MAX, Magnesium	237396,00
MAX, pH	122640,00
MAX, Bicarbonate	77964,00
MAX, Sulfate	55188,00
MAX, Sodium and Potassium	46428,00
MAX, Chloride	35916,00
MIN, pH	28908,00
MAX, Calcium	9636,00

As it shown in figure 6.1 above the top three of most significant impact on energy consumption are magnesium, bicarbonate and chloride content changes with minimal values of all other parameters makes. So, it can be said that content of these three impurities in raw water should be as low as it possible because it leads the most significant consumption when other water quality indicators are rather low. Moreover, it is seen that when the water is pretty clean, considerable rise of any impurity concentration leads to rise of energy consumption independent of other parameters. The indicators with maximal and pH with minimal parameters, instead, have the least impact. It shows that the energy consumption will be much bigger anyway and there is no reason to try to save on some certain impurity leaving it in the water because it does not affect the final energy consumption anyway.

## 6.2 Equipment

Here are some words about kinds of pumps which are more exposed to influence of raw water quality indicators changes than others. To assess this, I decided to show frequency of cases when one or the other pump type was the reason of incline in energy consumption of water treatment. And the easiest way to show it is to summarize differences for all sets of data and sort in descending order, how it is shown in the table 6.2 below.

Table 6.2. Contribution in energy consumption by pumps type

Pumps of clarified water, kW*h/a	2417760
Lime dosing pumps, kW*h/a	973236
Recirculation pumps of lime, kW*h/a	727080
Sludge water pumps, kW*h/a	113880
Coagulant dosing pumps, kW*h/a	79716
Pumps of mechanical filters rinse water reuse, kW*h/a	57816
Recirculation pumps of coagulant, kW*h/a	35040
Pumps of ion-exchange filters internal needs of 1st stage, kW*h/a	12264
Standart degasser blower, kW*h/a	0
Acid dosing pumps, kW*h/a	0
Caustic dosing pumps, kW*h/a	0
Pumps of degassed water, kW*h/a	0
Pumps of mechanical filters loosening, kW*h/a	0
Pumps of ion-exchange filters internal needs of 2nd and 3d stages, kW*h/a	0

It is clearly seen that the most influence caused by pumps of clarified water, they are the biggest one and exposed influence almost every water quality indicator change. On the second and third places the lime dosing and recirculating pumps are. And it is not unexpected neither, because as it was said in previous chapters, these pumps energy consumption is a function of dose of lime, which in turn is a function of two, the strongest affecting, indicators: magnesium and bicarbonate. Further pumps groups affect easier and we can say for sure that almost there is no impact on the 1<sup>st</sup>, 2<sup>nd</sup> and 3<sup>rd</sup> stages of water treatment. Actually, only pre-treatment is exposed to fluctuations in raw water quality. I would like to repeat the main outcomes:

- the strongest impact on energy consumption is caused by water quality indicators change when the water is clean enough
- there is not the reason to try to spare by selective impurities treatment, the complex way will cost (consume energy) the same
- only water pre-treatment stage is exposed impact of water quality change.

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