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## ANALYSIS OF WATER TREATMENT METHODS FOR CIRCULATING WATER SUPPLY IN INDUSTRIAL PLANTS


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### ANALYSIS OF WATER TREATMENT METHODS FOR CIRCULATING WATER SUPPLY IN INDUSTRIAL PLANTS

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**Abstract:** This scientific paper deals with the problem of extracting  $Ca^{2+}$  and  $Mg^{2+}$  salts from water in order to prevent the formation of scale on the heating surfaces of heat exchange equipment. The features, advantages and disadvantages of chemical, membrane and ion exchange methods of water treatment have been evaluated. It has been shown that the chemical method of water purification can be used only for the preparation of industrial water at large stations (at the same time, high residual hardness prevails in the water, the equipment has low productivity), and the membrane method requires pretreatment of water, creation of overpressure and the inability to regenerate the membrane. The ion-exchange method, despite its inherent disadvantages, is the most promising, since this method does not form sediment, which must be removed with the help of additional devices, does not form sludge, there is a possibility of restoring ion exchange capacity, as well as the compact size of the installation, ease of maintenance and high efficiency.

**Keywords:** heat exchange, water softening, scale, reagent method, ion exchange, membrane, reverse osmosis.

**Аннотация:** Ишда иссиқлик алмашиини усқунасининг иситиладиган юзаларида қасмоқ пайдо бўлишининг олдини олиш учун сувдан  $Ca^{2+}$  ва  $Mg^{2+}$  тузларини олиш муаммоси кўриб чиқилган. Сув тайёрлашининг кимёвий, мембранали ва ион алмашиини усулларининг хусусиятлари, афзалликлари ва камчиликларига баҳо берилган. Сувни тозалашнинг кимёвий усули фақат йирик станцияларда саноат сувини тайёрлаш учун ишлатилиши мумкинлиги (бунда сувда юқори қолдиқ қаттиқлик ҳосил бўлади, усқуна паст унумдорликка эга бўлади), мембранали усул эса сувни дастлабки тозалаш босқичини, ортиқча босимнинг ҳосил қилинишини талаб этиши ва мембранани қайта тиклаш имкониятига эга эмаслиги кўрсатилган. Ўзига хос камчиликларга қарамай, сув тозалашнинг ион алмашиини усули энг мақбул ҳисобланади, чунки бу усул қўшимча қурилмалар ёрдамида олиб ташланиши керак бўлган чўкма ҳосил қилмайди, қуйқум ҳосил қилмайди, шунингдек ион алмашиини қобилиятини тиклаш мумкинлиги, қурилманинڭ ўлчамларини кичиклиги, техник хизмат кўрсатиши қулайлиги ва юқори самарадорликка эгалиги кўрсатилган.

**Таянч сўзлар:** иссиқлик алмашиини қурилмаси, сувни юмишатиш, қасмоқ, реагентли усул, ион алмашинуви, мембрана, тесқари осмос.

**Аннотация:** В работе рассматривается проблема извлечения из воды солей  $Ca^{2+}$  и  $Mg^{2+}$  с целью предотвращения образования накипи на греющих поверхностях теплообменного оборудования. Оценены особенности, преимущества и недостатки химического, мембранного и ионообменного методов подготовки воды. Показано что химический метод очистки воды может быть применен только для подготовки технической воды на больших станциях (при этом в воде преобладает высокая остаточная жесткость, оборудование обладают низкой производительностью), а мембранный метод требует предварительной обработки воды, создания избыточного давления и невозможностью регенерации мембраны. Ионообменный метод, не смотря на присущие ему недостатки, является самым перспективным, поскольку при этом методе не образуется осадок, который необходимо удалять при помощи дополнительных устройств, не образуется илам, существует возможность восстановления ионообменной способности, а также компактные размеры установки, простота в обслуживании и высокая эффективность

*Ключевые слова:* теплообменник, умягчение воды, накипь, реагентный способ, ионообмен, мембрана, обратный осмос.

### **Introduction**

In technology, for the efficient use of energy resources, the concepts of "energy saving" are used, which determines the achieved level of efficiency in the use of energy and energy resources, and "energy efficiency", which determines the economic indicator of the quality of use of energy and energy resources.

The main problem of recycling water supply systems in production companies is the process of scale formation and its deposition on the heating surfaces of heat exchangers, boilers, etc. Therefore, the energy efficiency of heat exchange equipment can be increased both by intensifying heat exchange processes using various design solutions (artificial roughness, swirling flow, etc.), and by neutralizing the formation of scale.

Practically every branch of industry has and is improving measures aimed at saving energy [1]. At industrial enterprises, one of the main sources of heat loss is heat exchange equipment, the main problem of which is the formation of scale on internal surfaces [2]. This problem is relevant not only for heat exchangers, but also for water supply systems and water treatment plants for CHP plants [3]. The formation of scale on the inner surface of the heat exchange equipment is the reason for the decrease in its efficiency, since scale is a rather strong heat insulator [4]. Due to the limited heat transfer of heating elements in conditions of scale formation, the heat exchanger operates in critical modes, which quickly leads to equipment failure and energy waste and, as a consequence, to financial losses [5].

No less important in the formation of scale is the problem of blockage of heat exchanger pipes (for example, a scale thickness of 1-2 mm can lead to a reduction in water throughput by 1/5).

Unfortunately, in industrial plants there is no way to continuously monitor the growth of scale in heat exchangers. The indicator of the growth of the scale layer is the change in the temperature regime of the heat exchanger [6], the deterioration of its thermal performance [7], as well as a decrease in its efficiency (scale with a thickness of only 2 mm practically halves the amount of transferred heat).

The scale structure, the degree of contamination of the inner surface of the heat exchanger and its type determine the method of cleaning them (mechanical, chemical, etc.), the choice of which depends mainly on the duration of the equipment shutdown, as well as the presence of reagents, special equipment, etc.

As a result of the use of the mechanical method, its negative sides are also manifested: a higher rate of scale formation due to an increase in the roughness of the heat exchange surface and a violation of the oxide protective layer, increased wear of equipment, large time costs, etc., and chemical cleaning can lead to partial dissolution oxide film and even the metal from which the heat exchanger is made [8].

To combat scale in heat exchange equipment, you need to know that it is entirely related to the hardness of water saturated with salts.

Continuous and long-term efficient use of heat exchangers is directly related to the degree of hardness of the water used [9].

### **Research Methods and the Received Results**

To extend the service life of heat exchangers, organize efficient and stable heat exchange, water must be softened as much as possible.

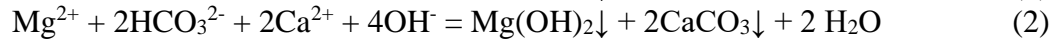
The processes of extracting  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  salts from water are called softening. There are many modern methods of water purification. The main ones are following:

- Chemical;
- Membrane;
- Ion exchange.

Consider the features of water preparation in the indicated ways.

**Water softening by chemical methods** is based on the treatment of water with soda ash, lime polyphosphates or complex compounds (for example, antiscalants), etc. Each of these methods involves the use of one or another reagent. Let's consider these methods in the presented sequence.

In industry, from the chemical methods of water softening, the most widespread is the soda-lime method, based on the addition of slaked lime and soda to the water [10]. These reagents form poorly soluble compounds with calcium and magnesium cations:  $Mg(OH)_2$ ,  $CaCO_3$ ,  $Ca_3(PO_4)_2$ ,  $Mg_3(PO_4)_2$ , etc., which precipitate [11]. Salts of carbonate hardness can be removed by adding slaked lime [12] (liming, treatment of water with calcium hydroxide  $Ca(OH)_2$  to a pH of about 10 with the formation of  $Ca^{2+}$  and  $OH^-$  ions in solution):

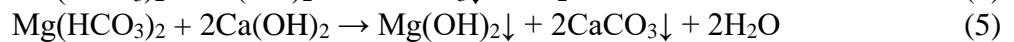
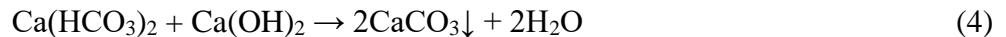


Ions  $Ca^{2+}$  and  $OH^-$  bind hydrogen ions and thereby cause a shift in equilibrium to the right. This, in turn, leads to the formation of  $CO_3^{2-}$  ions and their binding of  $Ca^{2+}$  ions to poorly soluble  $CaCO_3$ .

However, the introduction of  $OH^-$  ions into the solution leads to the binding of  $Mg^{2+}$  ions to poorly soluble magnesium hydroxide:



or in molecular form:



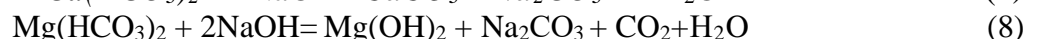
Dissolved  $CO_2$  is removed during a chemical reaction:



The above equations of chemical reactions show that in the process of formation and sedimentation of a precipitate, hardness salts are extracted from the solution, together with which colloidal and suspended particles with associated impurities are removed. Sedimentation occurs in sedimentation tanks and clarifiers with a suspended sediment layer [13].

However, this method does not completely eliminate the rigidity. The reason for this is the certain solubility of  $CaCO_3$  and  $Mg(OH)_2$ . Therefore, this method is used for relatively weak softening (up to 1.4 - 1.8 mg-eq / l) [14, 15]. The depth of water softening during soda-liming depends on the water temperature and, accordingly, is equal to 1-2 mg-eq / l without heating, and when the water is heated to 80-90 ° C - 0.2-0.4 mg-eq / l, respectively [16].

Under certain conditions, lime can be replaced with caustic soda using  $Na_2CO_3$  and  $NaOH$ :

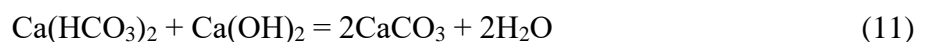


It is pertinent to note the formation of soda as a result of the reaction of caustic soda with bicarbonate, which means that its dosage is necessary. Therefore, water softening with caustic soda can be used if there is such a ratio between carbonate hardness, the content of free carbon dioxide and calcium non-carbonate hardness, when the amount of soda formed during the decomposition of bicarbonates and interaction with free carbon dioxide is sufficient to remove the calcium non-carbonate hardness, determined by equality:

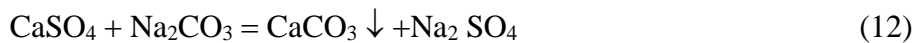


Where,  $H_{Ca}$  – calcium non-carbonate hardness of water to be softened;  $A$ — softened water alkalinity, mg-eq/l;  $H_c$  — carbonate hardness of water to be softened;  $CO_2$  — content of free carbon dioxide in the source water, mg-eq/l.

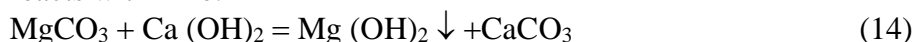
The above analysis shows that as a result of the addition of lime, the carbonate hardness decreases, but the non-carbonate hardness increases. Salts of non-carbonate hardness are removed by adding soda. Removal of carbonate hardness during water softening can be represented as the following chemical reaction:



Or molecular form:



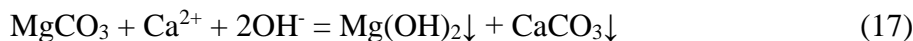
The resulting magnesium carbonate reacts with lime:



The amount of remaining hardness is only 0.3 meq/l. To increase the efficiency of the softening process, it is desirable to simultaneously add both lime and soda. With the simultaneous addition of reagents, the reactions proceed in the following sequence:



and further



Equation (17) shows that magnesium oxide hydrate  $\text{Mg}(\text{OH})_2$  coagulates and precipitates.

The reagent water treatment method is mainly used for use in heat exchangers [17]. Due to the high alkalinity of the reaction medium for drinking purposes, this method is not used.

*Polyphosphate method of water preparation.* For heat exchange equipment, in addition to water softening methods based on the use of chemical reagents, a softening method is also used with polyphosphates [18] that bind hardness salts. In industry, a method is more used that provides without the dosage addition of polyphosphates to the water (water seeps through filters with polyphosphates, which slowly dissolve and enter into a chemical reaction with hardness salts, which no longer form scale). Sodium polyphosphate  $\text{Na}_5\text{P}_3\text{O}_{10}$  can serve as such an effective reagent. In the case of using  $\text{Na}_5\text{P}_3\text{O}_{10}$ , the binding of  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  ions occurs due to the formation of calcium and magnesium compounds that are rapidly soluble in water:

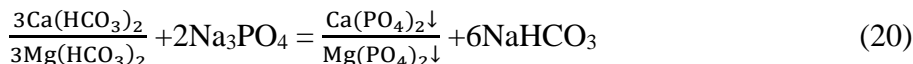


A significant disadvantage of this method of water softening is the impossibility of preparing drinking water and the possibility of causing harm to the environment if water softened by this method gets into water bodies.

*Method for softening water with sodium hexametaphosphate ( $\text{NaPO}_3$ )<sub>6</sub>.* Sodium hexametaphosphate ( $\text{NaPO}_3$ )<sub>6</sub> has surface active properties and, on this basis, can be adsorbed on the surface of nuclei of calcium carbonate crystals, leading to the isolation of  $\text{CaCO}_3$  particles, forming a thin film, which prevents the growth of microcrystal nuclei and, as a consequence, an increase in their solubility [19].

*Water softening method using trisodium phosphate ( $\text{Na}_3\text{PO}_4 \cdot 12\text{H}_2\text{O}$ ).* This method is based on the property of  $\text{Na}_3\text{PO}_4 \cdot 12\text{H}_2\text{O}$  to transfer scale to sludge [20]. As a result of the chemical reaction of trisodium phosphate with water, a slightly soluble calcium orthophosphate is formed, which is deposited on the faces of  $\text{CaCO}_3$  crystals, as a result of which their shape changes, which is an obstacle to the formation of larger crystalline aggregates. The use of this method of water softening contributes to the formation of easily removable sludge [21].

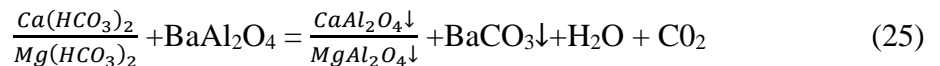
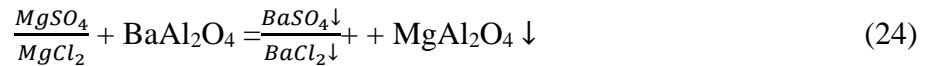
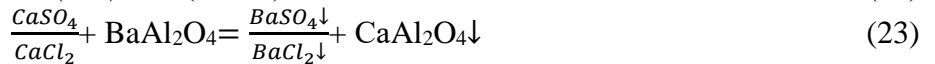
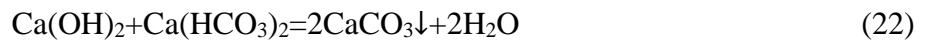
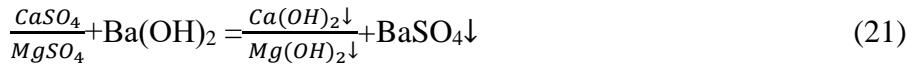
The chemical reaction of the water softening process with trisodium phosphate is represented by the equation:



The resulting calcium and magnesium salts of phosphate acid are poorly soluble in water, therefore they almost completely settle. Since this method is quite expensive, its use for water softening requires preliminary softened lime and soda [22].

*Water softening method using barium.* This method is used in combination with other methods. Barium-containing reagents such as  $\text{Ba}(\text{OH})_2$ ,  $\text{BaCO}_3$ ,  $\text{BaAl}_2\text{O}_4$  are preliminarily introduced into the water.

The introduction of BaCO<sub>3</sub> is coupled with the use of flocculants with mechanical stirrers, since it forms a heavy suspension that quickly settles [22, 23]. The stages of the chemical process are described by the reactions:



Barium reagents are toxic; therefore, this method is not suitable for the preparation of drinking water, and in industry it is used extremely rarely due to its high cost.

The analysis of water softening by reagent methods shows that they can be used only at large water treatment plants and exclusively for the preparation of industrial water, used, for example, in heat exchange equipment, since this method of water treatment is associated with the disposal of solid sediment, the presence of a specially equipped storage for reagents, availability of an optimal method for introducing reagents into water.

In addition, another disadvantage is the high value of the residual hardness of softened water [24]. Sedimentation is very slow, the performance of the equipment is low, and the dimensions are rather large. As a result of softening by this method, waste is formed in the form of difficult to dispose of sludge. The technological process of chemical water softening requires careful control, and mainly manual (laboratory), since it depends on many factors: water temperature, dosage accuracy of reagents, etc. [13].

**Water purification using membranes** — is based on water filtration through specially prepared materials having certain pore sizes [24]. The water to be purified is passed through a special semi-permeable membrane with many tiny pores. Under the influence of pressure, water penetrates through the membrane [25]. As a result, all impurities remain on one side of the membrane, and purified water on the other. The membrane preparation method can be used to purify water from impurities of mechanical and organic origin. The quality of purification by the membrane method depends entirely on the material of the membrane [26]. As materials for membranes can be used: polymers of natural origin, synthetic polymers, ceramics, composites, silicate glasses, etc.

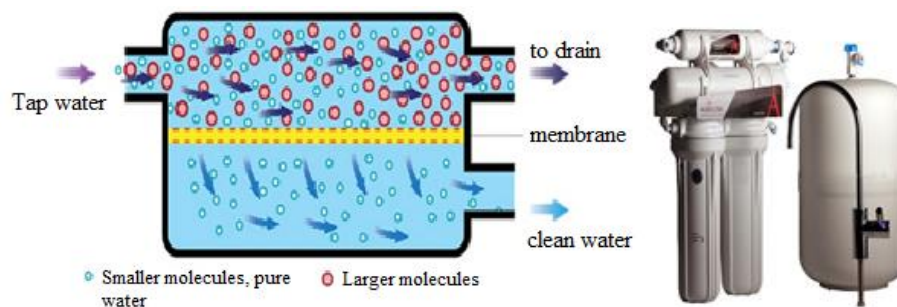


Fig. 1. Reverse osmosis plant.

Analyzing individual methods of membrane filtration of water.

Membrane water softening methods include an installation operating on the principle of *reverse osmosis* (Figure 1, 2), when the pore size of the film material does not exceed the size of water molecules. In this case, mainly water and some part of salts, the ion size of which does not exceed 0.0001 microns, can pass through the trap. Using this method, it is possible to filter out both organic and inorganic contaminants, achieving a high degree of salt removal at low energy costs [27, 28].

The main advantages of reverse osmosis plants are: a high degree of water purification (up to 99.9%) without heating and the use of chemical reagents from organic impurities, compact size, low energy costs, the possibility of using in microelectronic, food, pharmaceutical and other industries, low operating costs.

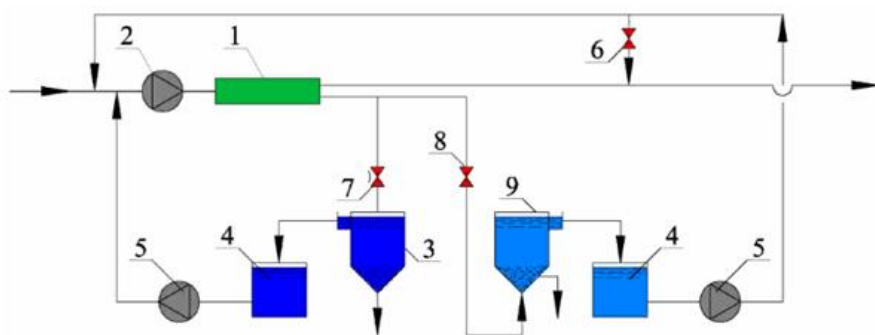


Fig. 2. Technological scheme for softening groundwater:

1– membrane apparatus; 2 – pump; 3 – sump for collecting wash water; 4 – collection of water; 5 – pump; 6-8 – valves; 9–reactor.

Along with the indicated advantages, there are also significant disadvantages of the installation, consisting in the high cost of the installation, the impossibility of using purified water for drinking purposes and high requirements for the quality of the water to be softened.

*Nanofiltration* method of water treatment, flowing under pressure in the range of 3 - 20 bar, allows you to filter out larger particles of impurities than with reverse osmosis. When cleaning by this method, the composition of salts in water before and after cleaning does not change, the color and turbidity may decrease. Surface waters are purified by nanofiltration.

*The ultrafiltration* method of water preparation is based on the use of a filter module with capillary sizes from 0.001 to 0.01 microns. The module is usually made of polyethersulfone and the filtration process takes place at a pressure of 1.5 to 7 bar.

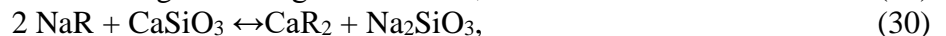
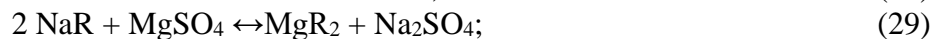
The main disadvantages of the membrane method of water softening can be considered the need for primary filtration, the creation of excess pressure in the system for pushing water through the membrane, the inability to regenerate the membrane, the relative high cost of reverse osmosis plants and the requirement for additional costs [29].

**Water softening by ion exchange method.** From a practical point of view, in order to eliminate the main disadvantages of the above two methods of preparing water for technical needs, consisting in the need for primary filtration, creating a high pressure, lack of the possibility of regeneration, high residual hardness, excessively slow sedimentation of the sludge, low productivity of equipment and its high cost, the most preferable and economically justified is the ion exchange method, which excludes the formation of sediment and does not require continuous dosage of reagents, which greatly simplifies the operation of the installation, which has much smaller overall dimensions, but greater processing efficiency, compared to installations operating by the deposition method [30]. This method uses the ability of individual hardly soluble components, which are ion exchangers, to enter into exchange reactions with cations and anions contained in water [31]. Ion exchangers are substances prone to sorption exchange of ions with an electrolyte solution, insoluble but water-swelling solid granular inorganic substances or high-molecular organic compounds with a mobile cation ( $H^+$ ,  $Na^+$ ,  $K^+$ ,  $NH_4^+$ ) or anion ( $OH^-$ ). [32]. Cations are substances that exchange cations, and ion exchangers are substances that exchange anions. Cations have a certain capacity, determined by the

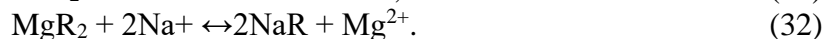


number of cations that it is able to exchange during the filtration cycle [33]. This capacity can be full exchange capacity, determined by the quantitative composition of calcium and magnesium ions, which is capable of retaining 1 m<sup>3</sup> of the cation exchanger until the moment of dynamic equilibrium (the equation of the filtrate hardness with the hardness of the source water), and working, determined by the ability to retain 1 m<sup>3</sup> of the cation exchanger until the moment of "breakthrough" into hardness ion filtrate. The absorption capacity is determined by the ratio of the volumetric capacity to the entire volume of the cation exchanger. When the working capacity of the cation exchanger is depleted, it must be regenerated [34]. The consumption of the treated water, its hardness and the characteristics of the resins used determine the frequency of regeneration of the cation exchanger, carried out with an aqueous solution of sodium chloride, which replaces calcium and magnesium ions with sodium ions. Among all the ion-exchange methods for the preparation of industrial water, the method of sodium cationization stands out [35]. In this method, ion-exchange materials exchange calcium and magnesium ions with ions of other substances that do not form scale on the heating surfaces of heat exchangers, boilers, etc. As the main reagent for the regeneration of the cation exchanger in the method, sodium chloride was chosen, which is characterized by its availability and low cost. Regeneration products (CaCl<sub>2</sub>, MgCl<sub>2</sub>) are satisfactorily soluble in water. [36]

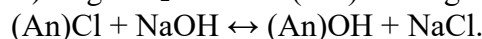
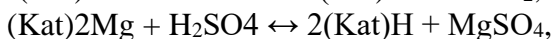
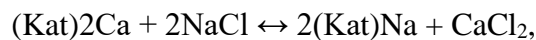
However, the processes of ion exchange are reversible [37]. Therefore, if an increase in sodium ions relative to calcium and magnesium ions is observed in water, the absorption of Ca<sup>2+</sup> and Mg<sup>2+</sup> in equations (26) - (30) slows down, and the process shifts more and more to the left.



This process can be depicted in the form of the following reactions:



If an increase in the concentration of sodium and potassium in water during the treatment of water leads to an increase in mineralization, then, even with two-stage sodium cationization, deep softening of water becomes almost impossible. Then there is a need for regeneration with solutions of the corresponding alkalis, acids and salts[31]:



An installation for water softening, with the principle of sequential use of H-cationization and OH-anionization, is shown in Figure 3.

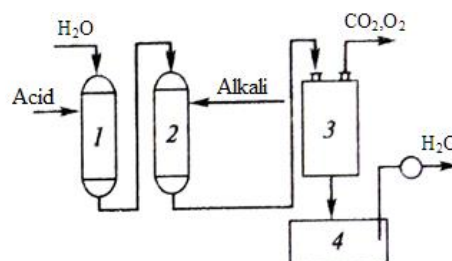


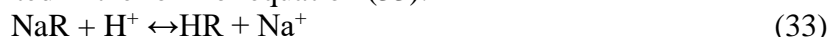
Fig. 3. Water softener.

1 – cation exchanger; 2 – anion exchange filter; 3 – degasser; 4 – collection of water.

However, increasing the efficiency of regeneration by increasing the concentration of the solution has a certain limit associated with economic costs (the need to reduce the consumption of the solution with



an increase in the concentration of sodium chloride), which leads to a decrease in the efficiency of regeneration [38]. To eliminate this disadvantage, it is necessary to use a two-stage regeneration scheme: at the first stage, they are regenerated with a dilute (2-3%), and at the second stage, with a sodium chloride solution with a higher concentration (10-12%). However, with a limited flow rate of the regeneration solution, its filtration rate never reaches the filtration rate of softened water. For the diffusion of  $\text{Na}^+$  ions into the cation exchanger core and  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  ions from the core into the solution, at least 15 minutes are required. This factor is decisive when calculating the maximum filtration rate of the regenerating solution, which is in the range of 4–6  $\text{m}^3/\text{h}$ . Since the intensification of ion diffusion is a function of temperature, then, if the process allows, the regeneration solution must be heated to  $40^\circ\text{C}$ . The exchange capacity of the cation exchanger in the sodium form depends on the hydrogen index of the water being softened [39]. With a decrease in pH, the number of  $\text{H}^+$  ions participating in the exchange with  $\text{Na}^+$  ions increases. This dependence can be represented in the form of equation (33):



In [41], to eliminate water hardness, a "cation-exchange" method based on the use of cation-exchange resins is proposed. According to this method, solids contain mobile ions called ion exchangers (insoluble in saline, acidic and alkaline media), which are capable of exchanging ions for the environment. The author of the work divides ion exchangers into two groups, in the first of which cations are exchanged for cations of the medium (cation exchangers), and in the second, ion exchangers exchange their anions (anion exchangers).

As inorganic ion exchangers, the author distinguishes zeolites - aluminosilicates with a complex composition (aluminosilicate  $\text{Na}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 4\text{SiO}_2 \cdot m\text{H}_2\text{O}$ ). The author allows the use of ion-exchange resins, which combine high operational and technical characteristics with a variety of physical and chemical properties.

The author of this work reflects the composition of the cation exchangers used for water softening in the form of a generalizing formula  $\text{Na}_2\text{R}$ , where  $\text{Na}^+$  is a very mobile cation, and  $\text{R}^{2-}$  is a cation exchanger particle with a negative charge. When water is passed through the cation exchanger, sodium ions are exchanged for calcium and magnesium ions. This exchange is expressed by the following equations:

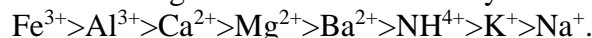


As a result, calcium and magnesium ions, passing from the solution to the cation exchanger, reduce the hardness of the water.

With the onset of dynamic equilibrium, the ion exchanger undergoes regeneration by passing a concentrated solution of  $\text{NaCl}$  ( $\text{Na}_2\text{SO}_4$ ) or  $\text{HCl}$  ( $\text{H}_2\text{SO}_4$ ). This leads to the release of  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  ions into the solution and saturation of the cation exchanger with  $\text{Na}^+$  and  $\text{H}^+$  ions.

In [42], for water softening, it is proposed to use natural (glauconites, humus coals) and artificial ion-exchange resins. The author of the work also subdivides these ion exchangers into cation exchangers, exchanging cations, and ion exchangers, exchanging anions. According to the author, ion exchangers consist of the same or different ionogenic groups, and cation exchangers can have mixed functional groups in the following combinations: sulfonic and oxyphenolic, sulfonic and carboxyl; phosphoric acid residues and oxyphenolic; arsenic and oxyphenolic; carboxyl and oxyphenolic. According to the degree of dissociation, the author subdivides ion exchangers into strongly acidic ones; weakly acidic; strongly basic and weakly basic.

On the basis of the studies carried out, the author notes the dependence of the rate of ion exchange during cationization on factors such as the valence of ions, their charge, the value of hydration, the efficiency of the ion radius and makes a series in decreasing order of the rate of entry of ions into the cation exchanger:



In the process of increasing the concentration of ions during the regeneration of cation filters, according to the author, this pattern can be changed.

The disadvantages of this method include periodic costs for the regeneration of chemicals, the need for wastewater treatment, an increase in operating costs with an increase in the salt content in the source water [43].

### Conclusion

The analysis of water treatment methods for water used for technical purposes that does not form scale on the heating surfaces of heat exchangers, boilers, etc., shows that the most effective is the ion-exchange method, which has found wide application in industry. The salts of magnesium and calcium, which impart hardness to water, are replaced by other chemical structures as a result of ion exchange, preserving the necessary properties of water [44]. This method of water treatment is also used in cases where it is necessary to prepare highly mineralized water with a salt content in the range of 100-200 mg per liter, and in cases with a sufficiently high level of hardness [45].

The advantages of the method include the ease of operation of the water treatment plant (WPU), the non-formation of sediment, which must be removed with the help of additional devices, the small dimensions of the apparatus, no sludge formation, which cannot be said about the chemical method, high processing efficiency compared to the installation of the chemical method, recovery the ion exchange capacity of the ion exchanger, in contrast to the membrane method, which, after filling the membrane, cannot be reused [46].

Thus, based on the above methods, we can conclude that the most convenient and profitable option for softening process water in heat exchangers is the ion-exchange method, which allows you to qualitatively soften water in a relatively short time.

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