Analysis of water softening methods and an algorithm of choosing the best method for using in production cycle

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Abstract. This article presents advantages and disadvantages of the most widespread water softening methods, such as reagent method, cation exchange softening, thermal method, reverse osmosis and electromagnetic softening. According to the application features and characteristics of each method, there was developed an algorithm that helps to choose water softening method in case of given specified parameters (turbidity, color, hardness) and the desired level of water hardness after treatment.

1. Introduction

Water hardness is one of the physical and chemical properties that can lead to adverse harmful effects for human beings. Water with high concentration of calcium carbonate has detrimental effects on the human body: damaging a fatty layer of skin, therefore skin is getting prematurely older; salts accumulation and the appearing of circulatory system diseases, joint problems, stones in the kidneys and biliary tract. Hardness salts build up limescale on household appliances [1]. In addition, using water with high level of hardness leads to increased energy consumption of household appliances due to the limescale, which in turn quickly disable them [2].

There are different types of water hardness: temporary, permanent, total, carbonate and non-carbonate. Total hardness includes the content of all calcium and magnesium salts. Carbonate type - the content of carbonates (within the limits of solubility) and hydrocarbonates \(\text{Ca(HCO}_3\text{)}_2\); \(\text{Mg(HCO}_3\text{)}_2\); non-carbonate – the content of other salts, basically chlorides and sulfates (\(\text{CaSO}_4\), \(\text{CaCl}_2\), \(\text{MgSO}_4\), \(\text{MgCl}_2\)). Temporary water hardness is the type, which is eliminated by boiling; permanent one – hardness remaining after boiling [3].

The unit of water hardness in Russia, according to the existing standards, is the level "degree of hardness °H". It is equal to the milligram-equivalent of cations \(\text{Ca}^{2+}\) and \(\text{Mg}^{2+}\) contained in 1 liter of water .1 mg-equivalent of \(\text{Ca}^{2+}\) is equal 20,04 mg/l; 1 mg-equivalent of \(\text{Mg}^{2+}\) = 12,15 mg/l.

There are other similar units, used in different countries. One of them is German degree °dH, that is equal 0,3566 °H [2].

To remove water hardness, there are three main methods of water softening:

- reagent method,
- cation exchange softening,
• thermal method.
  Reverse osmosis and electromagnetic softening are also some of the newest and modern methods.

2. Materials and methods
The best choice of water softening method is based on physical and chemical analysis, including determination of turbidity, hardness and temperature.

In case of high turbidity levels (more than 500 mg/l), it is necessary to remove suspended solids in advance for a better result of water purification. If level of turbidity is more than 400 mg/l and total hardness is more than 35 mg/l, then it is better to use reagent method [4, 5]. Reagents are added into water: lime - to eliminate carbonate and magnesian hardness; soda - to eliminate non-carbonate hardness. This method is used for superficial softening when it is necessary to clarify turbid water of surface sources simultaneously.

Advantages of the method:
• high level of water purification and softening;
• harmful impurities are removed and turbidity is reduced.

Disadvantages:
• formation of processed products in the form of solid particles;
• strict compliance with the maximum dosage must be respected;
• such water is unsuitable for drinking, the exception is water after softening by soda or salt reagent [6].

If water contains salt Ca(HCO₃)₂, and turbidity indicators is around 5-8 mg/l, then the thermal method is used [7]. The water is heated above 100°C, which removes all carbonate and part of non-carbonate hardness in water in the form of gypsum CaSO₄.

Advantages of the method:
• simplicity of the procedure;
• there is no need for the purchase and subsequent maintenance of special equipment for filtration.

Disadvantages:
• this method is not suitable for softening large amount of water;
• after water treatment, there is a precipitate, which must be removed [6, 7].

Reverse osmosis is used when level of suspended solids is up to 6 mg/l.

It is based on the use of partially permeable membranes, that easily export water through and at the same time retain from 90 to 99% of hydrated salt ions, as well as other organic and mineral dissolved compounds, the smallest colloidal impurities, bacteria and viruses.

Advantages of the method:
• high level of water purification;
• the content of solid particles, inorganic substances and parasite cysts decreases;

Disadvantages:
• membranes are quickly clogged with heavy metal compounds, therefore, water must be pre-cleaned;
• reduces the content of useful minerals;
• expensive installations requiring high level of professional maintenance [3].

If it is necessary to reduce the hardness to 0.01 mg/l, it is recommended to use the cation exchange water softening, based on H- and Na-cation exchange filters:

one-step Na- cationization.

Softened water is passed through Na-cation exchange filters. It is used for deep water softening with a color level of not more than 30 degrees, turbidity - no more than 5-8 mg/dm³, total hardness of water up to 15 mg-eq/dm³.

Advantages of the method:
• this scheme allows to avoid acid drainage formation and, as a result, to use of acid-resistant equipment and materials.
Disadvantages:
- level of water softening is no more than 0.05 mg-eq / l;
- incomplete use of the working exchange capacity of the filter;
- increased salt consumption for regeneration.

Two-step Na-cationization.
Firstly, initial water is passed through the 1st stage of Na-cation exchange filters, where the hardness is reduced by 70-75%, and then through the 2nd stage of Na-cation exchange filters. It is used for quite deep water softening with a color level of no more than 30 degrees, turbidity - no more than 5-8 mg / dm³, total hardness of water from 8-10 mg-eq / dm³ up to 14 mg-eq / dm³.

Advantages of the method:
- deeper water softening;
- salt saving;
- filtration cycle increasing.

Disadvantages:
- limited water filtration rate;
- expensive and cumbersome method.

H-Na-cationization.
Softened water is passed through H and Na-cation exchange filters, and then both streams are mixed. It is used for water with turbidity level - no more than 5-8 mg / dm³ and with total hardness of water up to 14 mg-eq / dm³.

Advantages of the method:
- reduction of the working capacity of cation exchange filters contaminated with sulphonated carbon during water treatment with a predominant non-carbonate hardness;
- decrease of the water softening efficiency with a high content of sodium salts.

Disadvantages:
- deep water softening with high hardness and a significant amount of sodium salts;
- good use of the absorption capacity of H-cation exchange filters.

The electromagnetic method is also used to soften the source water. [8]. This method includes using an electronic processor, which creates electromagnetic waves from powerful permanent magnets. They penetrate the water and make it softer.

Advantages of the method:
- remove old limescale;
- softening happens quickly without any system’s delay;
- good for increased water hardness;
- eco-friendly;
- there is no need for further maintenance.

Disadvantages:
- after electromagnetic softening method, the water is not suitable for using, it is necessary to apply a filter;
- significant power consumption.

3. Results
It is quite complicated for an untrained specialist to choose a suitable method from variety of considered water softening methods, in case of given parameters of water hardness or for choosing a method and softening technology for an existing production scheme.

To help with decision about softening method, authors have developed an algorithm that allows, for the given parameters of the source water, to choose softening method (figure 1).

Authors propose to consider baseline, that includes turbidity, color, hardness and the desired level of water hardness after softening by one or another method.
Figure 1. An algorithm of choosing water softening method.

4. Discussion
The water softening method must be chosen according to the conditions of future maintenance [9].

To purify hard water from a single source, it is economically feasible to use the reagent method, it has a greater effect when it is used on industrial level. Using such a technology in a household requires at least special equipment that allows water softening without permanent human attention.

The easiest method is thermal. However, boiling removes only the carbonate hardness, while the non-carbonate hardness remains unchanged, causing limescale on the equipment, which is unacceptable in water treatment for steam generating, boiler plants, and heat exchangers. It is possible to use this method in industrial conditions, in case of cheap heat source. Reverse osmosis is one of the most forward-looking and widely used method of water softening. This method is better to use in various production cycles, for example, in the food industry for the production of drinks, during production of
fruit and vegetable juices, reverse osmosis method is used also to gain highly pure water for medicine goals. Equipment for water treating by electromagnetic waves are characterized by their small dimensions, easing of installation and maintenance, environmental safety, low operating costs, that are perfect for using at home. Besides, treated water includes calcium and magnesium that are essential for people in certain doses. Another advantage of these devices is destruction of previously formed scales within 1-3 months.

The cation exchange method is recommended for softening groundwater and surface sources with a turbidity level of no more than 5-8 mg/l and a color of no more than 30 degrees. Therefore, people who live out of town, and who prefer to use boreholes for water supply, which are characterized by a high salt content, should use water softening installations with the use of cation exchange method, which are not difficult to operate. The use of the cation exchange method requires permanent regeneration of spent cation and anion exchangers, that increases the price of softened water.

5. Conclusion
The algorithm of choosing water softening method can be used in many types of industry, where are existed lots of requirements for water.

From the point of view of the authors, the most forward-looking water softening method in large volumes is reverse osmosis. Nowadays new membranes for this method are being developed, which are resistant to chlorine and high temperatures, and also eliminate the problem of water demineralization, that can allow to use reverse osmosis at home in future [10, 11].

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References
[1] Shimoda Y et al 2020 Association between percentage of obese people and water hardness in water purification plants. Obesity Medicine 19 100244
[2] Shishkin V 2019 Comparison of methods for determining total water hardness. Modern technologies in construction. Theory and practice 1 371-4
[3] Nushtaeva A 2019 Influence of additional cleaning on the hardness of drinking water. Education and science in the modern world. Innovation 4(23) 134-8
[4] Clauwaert P et al 2020 Electrochemical tap water softening: A zero chemical input approach. Water Research 169 115263
[5] Malanova N V, Korobochkin V V and Kosintsev V I 2014 The Application of Ammonium Hydroxide and Sodium Hydroxide for Reagent Softening of Water. Procedia Chemistry 10 162-67
[6] Asonov A 2007 Calculation of cationic installations for water softening in industrial boilers. (Yekaterinburg: UrGUPS)
[7] Gryta M 2010 Desalination of thermally softened water by membrane distillation process. Desalination 257(1-3) 30-5
[8] Sanjuán I et al 2019 Electrochemical water softening: Influence of water composition on the precipitation behavior. Separation and Purification Technology 211 857-65
[9] Isakov V G, Vologdin S V, Ponomarev D S and Dyagelev M Y 2019 Modeling and system analysis of drinking water parameters in urban water supply systems IOP Conference Series: Materials Science and Engineering 537(6) 062045
[10] Ivanov V 2003 Water supply of industrial enterprises: A textbook (Saint-Petersburg: PGUPS)
[11] Micari M et al 2020 Towards the implementation of circular economy in the water softening industry: A technical, economic and environmental analysis. Journal of Cleaner Production 255 12029