ECONOMICAL AND ENVIRONMENTAL BENEFITS OF POINT-OF-USE NaCl BRINE REUSE BY NEW MEMBRANE TECHNOLOGY

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Cation exchange water softening is one of the most widely used technologies of water treatment. However, its environmental impact related to discharge of highly concentrated regeneration brine draws more attention as overall quality and availability of water resources decreases. Bearing in mind high levels of reusable NaCl in brine discharge, technology that will reduce the environmental impact and help reuse brine is required. To develop such technology composition of spent brine solution from Na-cation exchanger was investigated and conditioning of such solution with use of nanofiltration membranes of different types under different temperatures, pressures and recovery values was tested. Results show that optimal conditions for NaCl recovery include usage of DuPont (Dow) Filmtec Fortilife XC-N membrane elements at temperature 23-27 °C, pressure of 23-25 bar and recovery of 55-60 %. Under these conditions purity of NaCl in permeate over 90 % and productivity by NaCl of 13.1 kg/h were achieved. Principal technological scheme of the process of membrane conditioning of the spent regeneration solution was proposed that allows achieving reduction of NaCl consumption by 40 % and reduction of NaCl discharge into sewage by 72 % with corresponding economic and environmental benefits.

Keywords: membrane technology, softening, brine, sodium chloride, nanofiltration

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1. Introduction

Water softening with Na-cation-exchange resins is very widespread technology. Based on data for 2016, total world production of ion exchange resins (IER) could be estimated as 625 000 m³, with Na-cation-exchange resins for water softening are nearly 50 % of them, or 312 000 m³. Total world consumption of NaCl in 2020 reached 270 million tons (Global salt production, 2020 | Statista, 2021), and authors estimate the amount of salt used for regeneration of Na-cationite softeners to be 11,4–18,3 million tons. Regarding the efficiency of regeneration, conclusion could be done that only 6.6 million tons were spent for regeneration and 4.8–11.7 million tons of NaCl depending on the regeneration ratio (Ion exchange regeneration methods, 2021) was directly discharged into wastewater as spent regenerant solution (SRS) wastewater.

Considered as low volume discharge (Alchin, 2016), this wastewater is characterized by high levels of salinity and mostly NaCl and thus becomes serious
environmental problem. There are several negative effects of Na excess, including soil salinization and decrease of efficiency of wastewater treatment facilities, especially small local ones (Grasso, 1992). Also, high levels of sodium are known to decrease the permeability of soil for water, thus leading to problems with drainage of treated wastewater. Another environmental hazard of sodium is linked with its ability to promote uptake of phosphorus by algae leading to more intense algae blooming of water bodies (Grasso, 1992).

Possible ways of reduction of these environmental issues include replacement of sodium chloride with potassium chloride that has no effect on algae and is not harmful for soil. Yet such replacement would increase cost of water softening up since potassium chloride is nearly twice as expensive as sodium chloride (Grasso, 1992). In addition, potassium causes problems with water drainage as well (Water Softeners and Septic Systems, 2008).

Another issue is that the excess of NaCl is paid for and then just discharged to sewage being an excess over stoichiometric quantity required for efficient regeneration (Ion exchange regeneration methods, 2021). More is added to the economical part of the problem, as we have to consider the environment taxes and fines paid for discharging saline wastewater in most of countries.

Regarding the environmental and economic benefits of reuse of spent brines, several attempts to propose the solution were made. Some of proposed solutions include chemical precipitation of calcium and magnesium with different reagents from brine with further filtration of residual NaCl solution (Kozlov, 2009). Disadvantages of such technologies are usage of high amounts of expensive reagents (Na₂CO₃, NaOH), need in additional equipment and high amounts of wet solid waste.

Another method includes nanofiltration treatment of brine solution with added sulfuric acid to achieve pH of solution as low as 2 in order to promote permeation of monovalent ions including Na⁺ and Cl⁻ to permeate and retention of ions of hardness in concentrate (Brigano et al., 1993). Being relatively efficient, such solution results in production of aggressive acidic waste which is more harmful and difficult to treat than the initial spent brine solution.

Having regard to, all mentioned above, need for technology of recovery NaCl from regeneration wastewater free of said disadvantages is obvious. The aim of this study was to develop technology for conditioning of spent regeneration solution from Na-cation exchanger with the use of new generation of nanofiltration membranes for partial recovery of NaCl and reduction of environmental damage and cost of softening of water.

2. Materials and Methods

2.1 Spent regeneration solution of Na-cation exchanger

The object of the research in this work is spent regeneration solution (SRS) that is produced at the stage of regeneration of ion exchange resin. In order to find out the composition of actual SRS and distribution of its constituents in time of regeneration and to prepare the model solution for further tests samples of SRS from regeneration of industrial Na-cation exchanger in UPCORE (ion exchange technology that utilizes downflow currents for service cycles and...
upflow currents for regeneration) design were taken at power plant 5 (PP-5) in Kyiv, Ukraine.

SRS consists of diluted NaCl brine (ca. 8%) with sodium partially replaced by calcium and magnesium during the regeneration process. The composition of the initial regeneration solution is given in table 1.

Table 1. Composition of the initial regeneration solution

| Parameter            | Units | Value |
|----------------------|-------|-------|
| Chlorides            | meq/l | 1470  |
| Sodium               | meq/l | 1452  |
| Total hardness       | meq/l | 18    |
| Calcium              | meq/l | 16.6  |
| Magnesium            | meq/l | 1.4   |
| Total iron           | mg/l  | 1.47  |
| Manganese            | mg/l  | 0.115 |
| Total dissolved solids| g/l   | 85.3  |

2.2 Nanofiltration membrane elements

Experiments were done with 3 types of nanofiltration membrane elements with different parameters as shown in Table 2.

Table 2. Characteristics of test membrane elements

| Parameter / Item            | FILMTEC NF270 | FILMTEC NF90 | FORTILIFE XC-N |
|-----------------------------|---------------|--------------|----------------|
| Purpose                     | Removing TOC and THM precursors with medium to high salt passage and medium hardness passage | Removing high percentage of salts, nitrate, iron and organic compounds (pesticides, herbicides and THM precursors) | Selective ion separation for higher water recovery and waste reclamation |
| Type and size               | Spiral wound membrane element, 4” × 40” |               |                |
| Operating Pressure, bar     | 4.8           | 4.8          | 4.8            |
| Maximum Operating Pressure, bar | 41           | 41           | 41             |
| Target Permeate Flow Rate, m³/d | 3.2          | 2.6          | 3.2            |
| Operating Temperature Limit, °C | 45           | 45           | 45             |
| pH Range                    | 2.11          | 2.11         | 3.10           |
| Stabilized Rejection, %     | > 97.0        | 98.7         | 99             |
| Test conditions             | 2000 ppm MgSO₄, 4.8 bar, 25°C, pH 8, 15% recovery. |               |                |
2.3 Pilot nanofiltration plant

Pilot plant with the scheme shown on figure 1 was used. Constant operation in recycling mode was chosen due to limited availability of feed stream that was prepared in batches for every test.

![Diagram of Pilot Nanofiltration Plant]

**Fig. 1. Principal technological scheme of conditioning of pilot plant for the spent regeneration solution:**

1 - tank for regeneration solution; 2 - centrifugal pump; 3 - mechanical filter; 4 - pump; 5 - rack of nanofiltration membranes; 6, 7, 8 - pressure gauges

Model brine solution is stored in the tank 1. By means of feed pump 2, the initial solution is pumped to the next stage – removal of mechanical impurities able to damage or clog the membrane elements by the polypropylene cartridge (PPC) filter 3.

Further, model solution is pumped by high pressure pump 4 to the rack of pressure vessels with nanofiltration membrane elements 5. As model solution contained significant levels of chlorides, vertical centrifugal pump with titanium housing and working parts was used. As membrane separation took place, flows of permeate and concentrate occurred which were passed back to the tank 1. To achieve higher recovery for the system keeping recovery per element as low as the allowed limit concentrate recycle was implemented and part of concentrate stream leaving the membrane rack is sent back to the inlet of high-pressure pump.

Flowrates and pressures of each stream were measured with flowmeters and pressure gauges 8 respectively and controlled by adjusting the flow of recycle and concentrate with valves. Temperature of feed solution was measured by thermometer and controlled by heating up the solution via recirculation with feed pump 2.

2.4. Selection of most suitable element and comparison criteria

In order to select the most suitable membrane element and find the best conditions for recovery of NaCl from model solution several tests were done for all 3 membrane elements to investigate the effect of the main parameters of the process: temperature, recovery and pressure.
The comparison criteria for choosing the most effective membrane element were the values that characterize the purity of NaCl in permeate ($\alpha$) and the NaCl production in the permeate ($\beta$) calculated by the following equations:

\[ \alpha = \frac{C_{Na^+}}{C_{Cl^-}} \times 100 \% \] (1)

\[ \beta = \omega \cdot C_{NaCl} \] (2)

where $\alpha$ is the purity of the permeate by NaCl,%; $C_{Na^+}$ – concentration of sodium ions in permeate, meq/l; $C_{Cl^-}$ – concentration of chloride ions in permeate, meq/l; $\beta$ – NaCl output in permeate, kg/hour; $\omega$ – production of permeate, l/hour; $C_{NaCl}$ – concentration of NaCl in permeate, kg/l.

2.5. Method of estimation of economic and environmental efficiency

For the estimation of the environmental and economic efficiency of the proposed technology absolute ($\Delta$) and relative ($R$) indices of reduction of consumption and discharge of NaCl were calculated:

\[ \Delta = a - b \] (3)

where $\Delta$ – absolute index of reduction of cost and discharge of NaCl, units; $a$ - value of the parameter after the Na-cation exchange filter with the UPCORE technology (without brine reuse); $b$ - value of the parameter achieved with usage of the proposed technology.

\[ R = \frac{a - \Delta}{a} \times 100 \% \] (4)

where $R$ – relative indicator of reduction of cost and discharge of NaCl, %.

Calculations of savings on environmental payments were done based on estimation of cost of discharge of wastewater with excess of concentration of different compounds used by Ukrainian government (On Drinking Water and Drinking Water Supply, 2017). Estimation is performed by calculation of excess of concentration of a component:

\[ EC = \frac{C_c - L_c}{L_c} \] (5)

where $EC$ is excess of concentration; $C_c$ – actual concentration of a component; $L_c$ – limit of concentration for a component in wastewater allowed to be discharged into municipal sewage system (stated by government). It should be noted if value calculated by (5) is bigger than 10, $EC$ is taken to be 10 (On Drinking Water and Drinking Water Supply, 2017). Then payment for discharge is calculated as follows:

\[ P = V_D \times EC \times T \times F_{OL} + T \times V_D \] (6)

where $P$ is total payment for discharge; $V_D$ – volume of discharge of wastewater; $EC$ – excess of concentration; $T$ – tariff for discharge per 1 m$^3$ of wastewater; $F_{OL}$ – coefficient of increase of tariff for excess of concentration (stated as 59 %).

Then total annual payments were calculated for cases without technology of brine reuse based on 292 regenerations of softener per year (operational data from plant) and with proposed technology and savings were found using the formula (6).

To estimate payback period for proposed technology the following formula was used:

\[ PP = \frac{CapEx}{S_{NaCl} - \sum OpEx + S_{ENV}} \times 12 \] (7)

where $PP$ is payback period in months; $CapEx$ – total capital expenses for implementation of proposed technology; $S_{NaCl}$ – annual savings on cost of NaCl by its reuse; $\sum OpEx$ – total amount of operational expenses for proposed technology (power
cost, maintenance, consumables etc.); $S_{ENV}$ – savings of environmental payments due to decrease of wastewater volume discharged to municipal system.

3. Results and Discussion

3.1. Analysis of SRS from industrial Na-cation exchanger and determination of composition of the model solution

In order to prepare the model solution for further tests of the process of conditioning of SRS the analysis of the spent regeneration solution discharged during the regeneration stage of the Na-cation exchanger at the PP-5 in Kyiv was carried out.

In order to determine the amount of wastewater that is appropriate for averaging and subsequent conditioning, an initial concentration profile for the Na-cation-exchange filter regeneration process, shown in Fig. 2, was drawn.

As it could be seen from the concentration profile of regeneration, main quantity of the target species – sodium – appears in the discharge between 10 and 70 m$^3$ of wastewater. For the regeneration of the ion exchange resin in the Na-cation exchanger 31 m$^3$ of 8 % solution of NaCl is used. Consequently, in order to obtain the required volume of solution provided nearly 50 % of recovery of membrane plant, it is necessary to take and condition 60 m$^3$ of SRS. Estimation could be done that wastewater between 10 and 70 m$^3$ of regeneration discharge should be collected for reuse and to obtain the required amount of NaCl its reuse should be at least 80 %. After averaging this
volume, the average value of the TDS of 56 g/l is achieved.

Regarding the mentioned above, the composition of model solution for tests was calculated to correspond to the average discharge of the industrial Na-cation exchanger. The composition of the model solution is shown in table 3.

| Parameter | Units of measurement | Value |
|-----------|----------------------|-------|
| TDS       | mg/L                 | 56650 |
| pH        | units                | 7.14  |
| Chlorides | meq/L                | 806.9 |
| Calcium   | meq/L                | 282.5 |
| Magnesium | meq/L                | 87.5  |
| Total hardness | meq/L | 370   |
| Sodium    | meq/L                | 437   |

Table 3. The composition of the model solution

3.2. Selection of the most suitable membrane element for the separation of NaCl from SRS

To select the most suitable membrane element, three different membrane elements were tested. Choice of the membrane element was carried out at constant temperature and pressure. Table 4 shows parameters and results of the test runs. Characteristics of permeate and concentrate obtained during tests are given in table 5.

Results of the experiment as comparison criteria are shown at the figure 3.

Table 4. Parameters and results of the tests of membrane elements

| Membrane element | Conditions | Results | Recovery, % |
|------------------|------------|---------|-------------|
|                  | Pressure, bar | Temperature of solution, °C | Flow rate, l/h | Permeate | Concentrate |         |
| FILMTEC NF270    | 25.0        | 23      | 330 300     | 52%     |
| FILMTEC NF90     | 25.0        | 23      | 60 300      | 17%     |
| FORTILIFE XC-N   | 24.0        | 23      | 300 300     | 50%     |

Table 5. Composition of permeate and concentrate obtained from various membrane elements

| Membrane element | Sample | TDS, mg/l | pH  | Chlorides, meq/l | Total hardness, meq/l | Sodium, meq/l |
|------------------|--------|-----------|-----|------------------|-----------------------|---------------|
| FILMTEC NF270    | Permeate | 33050     | 6.86| 465              | 95                    | 370           |
|                  | Concentrate | 65200 | 7   | 850              | 515                   | 335           |
| FILMTEC NF90     | Permeate | 14500     | 6.54| 210              | 19                    | 191           |
|                  | Concentrate | 53200 | 7.18| 740              | 395                   | 345           |
| FORTILIFE XC-N   | Permeate | 29750     | 7.04| 410              | 35                    | 375           |
Analysis of the obtained results shows that the largest NaCl yield in permeate (7.08 kg/h) is observed for NF-270 but its purity is 79.57%. On the other hand, for NF-90 NaCl yield in permeate is substantially lower — 0.66 kg/h, but the purity of NaCl in permeate is 90.95%.

FORTILIFE XC-N element was the most effective for the separation of NaCl from SRS, demonstrating high NaCl yield in permeate (6.53 kg/h) combined with high purity (91.46%).

Regarding these results, FORTILIFE XC-N was selected for further research.

3.3. Choosing the optimal conditions for process of conditioning of SRS on FORTILIFE XC-N membrane element

To determine the optimal conditions for SRS conditioning process on FORTILIFE XC-N membrane element, a study was made of the effect of the main parameters of the separation process — temperature, recovery and pressure.

To investigate the influence of temperature, range from 20 °C to 30 °C was chosen as easy to achieve and control and corresponding to typical temperatures of pressure driven membrane separation processes. Parameters of the process and the results of the study of temperature influence are given in tables 6 and 7 respectively.
Table 6. Conditions for the process of choosing the optimal temperature

| Conditions | Results |
|------------|---------|
| Pressure, bar | Temperature of solution, °С | Flow rate, l/h | Recovery, % |
| 24.0 | 20 | 390 | 240 | 62 |
| 24.0 | 23 | 420 | 264 | 62 |
| 24.0 | 25 | 435 | 270 | 62 |
| 24.0 | 27 | 450 | 276 | 62 |
| 24.1 | 30 | 468 | 288 | 62 |
| 24.0 | 32 | 480 | 300 | 62 |

Table 7. Composition of permeate and concentrate obtained at different temperatures

| Temperature of solution, °С | Sample | TDS, mg/l | pH | Chlorides, meq/l | Total hardness, meq/l | Sodium, meq/l | α, % | β, kg/h |
|-----------------------------|--------|-----------|----|-----------------|----------------------|---------------|------|---------|
| —                           | Model solution | 53050 | 6.94 | 812 | 367.5 | 445 |
| 20                          | Permeate | 37300 | 6.89 | 553 | 69 | 484 | 87.53 | 10.95 |
|                             | Concentrate | 71450 | 6.89 | 1091 | 715 | 376 |
| 23                          | Permeate | 41150 | 6.76 | 560 | 70 | 490 | 87.51 | 11.94 |
|                             | Concentrate | 76550 | 7.04 | 1091 | 685 | 406 |
| 25                          | Permeate | 37600 | 7.12 | 545 | 71 | 474 | 86.97 | 11.96 |
|                             | Concentrate | 75150 | 6.90 | 1117 | 715 | 402 |
| 27                          | Permeate | 39400 | 6.89 | 572 | 74 | 498 | 87.07 | 13.01 |
|                             | Concentrate | 77350 | 7.06 | 1091 | 710 | 381 |
| 30                          | Permeate | 38275 | 6.91 | 559 | 82 | 477 | 85.34 | 12.95 |
|                             | Concentrate | 72450 | 7.00 | 1091 | 720 | 371 |

Figure 4 shows dependence of the yield of NaCl in permeate (β), as well as its purity (α) on the operating temperature.

Results of the study show that temperature significantly affects purity of NaCl in permeate while having less impact on the yield. Consequently, with increasing temperature it is possible to obtain a slightly larger amount of sodium chloride in permeate, but the purity will be significantly lower.

As seen from the graph, the optimum point is a temperature of 24 °C, which provides purity of salt of 87.5 % with a relatively high yield in permeate – 12 kg/h. The results are in good agreement with well-known effect of temperature on the efficiency of the membrane separation process.

It was determined that the optimal temperature for the process of purifying the SRS can be considered as a range of 23-27 °C, where average values of comparison criteria are: α = 87.2 %, β = 12.3 kg/h.

Following experiments were carried out to study the influence of recovery on the process of conditioning of SRS. Parameters of the process and results are shown in tables 8 and 9 respectively. Composition of permeate and concentrate, obtained at different recovery values, are given in table 9.
**Fig. 4.** Dependence of the purity of permeate on NaCl (α) and the NaCl yield in permeate (β) on the temperature

**Table 8. Conditions for conducting the selection process of the recovery**

| Pressure, bar | Temperature of solution, °C | Flow rate, l/h | Recovery, % |
|---------------|-------------------------------|----------------|-------------|
|               |                               | Permeate | Concentrate |                  |
| 23.0          | 26                            | 465     | 450         | 50.8           |
| 23.5          | 26                            | 480     | 324         | 59.7           |
| 24.3          | 26                            | 438     | 216         | 67.0           |

**Table 9. Composition of permeate and concentrate obtained for different recovery**

| Recovery, % | Sample          | TDS, mg/l | pH   | Chlorides, meq/l | Sodium meq/l | Total hardness, meq/l | α, %  | β, kg/h |
|-------------|-----------------|-----------|------|------------------|--------------|-----------------------|-------|--------|
| —           | Model solution  | 56650     | 7.14 | 806.9            | 437          | 370                   |       |        |
| 50.8        | Permeate        | 40700     | 6.81 | 532.9            | 469          | 64                    | 87.99 | 12.65  |
|             | Concentrate     | 74500     | 7.01 | 1015.0           | 505          | 510                   |       |        |
| 59.7        | Permeate        | 39825     | 6.74 | 576.5            | 504          | 73                    | 87.34 | 14.02  |
|             | Concentrate     | 77200     | 6.88 | 1116.5           | 417          | 700                   |       |        |
| 67.0        | Permeate        | 42175     | 6.67 | 578.6            | 491          | 88                    | 84.79 | 12.46  |
|             | Concentrate     | 78150     | 6.76 | 1167.2           | 407          | 760                   |       |        |
Figure 5 shows dependence of recovery on comparison criteria. It could be concluded that with the growth of recovery there is a significant decrease in quality of the obtained purified sodium chloride solution, and the effect on NaCl yield in permeate is best described by a parabolic curve.

**Fig. 5. Dependence of recovery on the purity of the permeate by NaCl (α) and the NaCl yield in the permeate (β)**

Increase in recovery leads to increase in the average concentration of dissolved substances, and in addition, increases the intensity of the concentration polarization — the concentration of salts on the surface of the membrane. All this leads to a drop of selectivity and specific productivity.

Thus, from the analysis of the obtained graphical dependence, we can conclude that the optimal values of the recovery for these conditions will be 57 %.

Next, a study was conducted to determine the efficiency of the separation of sodium chloride from SRS at different feed pressure values. Conditions and results of the process are shown in the table 10.

Characteristics of samples of permeate and concentrate obtained at different pressure values are given in Table 11.
Table 10. Conditions for the process of choosing the optimal pressure

| Conditions | Results |
|------------|---------|
| Pressure, bar | Temperature of solution, °C | Flow rate, l/h | Recovery, % |
|             |                     | Permeate | Concentrate |         |
| 20.2        | 27                  | 425     | 321         | 57      |
| 22.0        | 27                  | 441     | 333         | 57      |
| 23.5        | 27                  | 448     | 337         | 57      |
| 24.3        | 27                  | 457     | 345         | 57      |
| 25.1        | 27                  | 467     | 353         | 57      |

Table 11. Composition of permeate and concentrate obtained at different pressures

| Pressure, bar | Sample | TDS, mg/l | pH | Chlorides, meq/l | Sodium, meq/l | Total hardness, meq/l | a, % | b, kg/h |
|---------------|--------|-----------|----|------------------|---------------|-----------------------|------|--------|
| 20.2          | Permeate | 35554    | 6.71| 496              | 439           | 62                    | 88.58| 11.36  |
|               | Concentrate | 66577    | 6.98| 968              | 507           | 512                   |      |        |
| 22.0          | Permeate | 40700    | 6.81| 540              | 469           | 64                    | 86.75| 12.32  |
|               | Concentrate | 74500    | 7.01| 1029             | 505           | 510                   |      |        |
| 23.5          | Permeate | 39825    | 6.74| 585              | 504           | 73                    | 86.11| 13.46  |
|               | Concentrate | 77200    | 6.88| 1132             | 417           | 700                   |      |        |
| 24.3          | Permeate | 42175    | 6.67| 587              | 491           | 88                    | 83.60| 13.49  |
|               | Concentrate | 78150    | 6.76| 1184             | 407           | 760                   |      |        |
| 25.1          | Permeate | 44178    | 6.89| 616              | 499           | 89                    | 81.03| 13.89  |
|               | Concentrate | 82727    | 7.02| 1202             | 401           | 772                   |      |        |

From the obtained graphic dependence, shown on figure 6, conclusion could be done that with increase of pressure there is a gradual increase in NaCl content in permeate (β), but the purity of the permeate by NaCl (α) is described by the inverse response.

Obtained results allow to formulate optimal conditions for the process of conditioning of SRS:
- membrane element - FORTILIFE XC-N;
- temperature - 23-27 °C;
- recovery – 57 %;
- pressure - 24,1 bar.

Subsequently, under these conditions, the efficiency of the process of conditioning on the pilot unit was evaluated.

3.4. Estimation of efficiency of the conditioning process under optimum conditions at the pilot unit

Then, a test was carried out on the efficiency of the separation of sodium chloride from SRS under optimum conditions at the pilot plant, given in Table 12.

As a result of the test samples of permeate and concentrate, the characteristics of which are given in Table 13.
Fig. 6. Dependence of pressure on the purity of the permeate by NaCl (\(\alpha\)) and the NaCl output in the permeate (\(\beta\))

**Table 12. Conditions for conducting the process of conditioning on the pilot plant**

| Conditions | Results |
|------------|---------|
| Pressure, bar | Temperature of solution, °C | Flow rate, l/h | Recovery, % |
| 24.0 | 24 | Permeate 480 | Concentrate 360 | 57.1 |

**Table 13. Composition of permeate and concentrate obtained under optimal conditions**

| Type of solution | TDS, mg/l | pH | Chlorides, meq/l | Total hardness, meq/l | Sodium, meq/l | \(\alpha\), % | \(\beta\), kg/h |
|------------------|-----------|----|------------------|-----------------------|---------------|---------|-------------|
| Model solution   | 57850     | 7.07 | 912.5           | 367.5                 | 445           |         |             |
| Permeate         | 41173     | 6.84 | 516.6           | 45                    | 472           | 91.4    | 13.1        |
| Concentrate      | 81131     | 7.15 | 984.6           | 585                   | 400           |         |             |

3.5. Principal technological scheme of conditioning of SRS

Obtained results of the experiment of the process of conditioning of the spent regeneration solution allow offering the scheme for increasing the economic feasibility and environmental safety of the Na-cation-exchange softening process, shown in Fig. 7.
Fig. 7. Principal technological scheme of the process of SRS conditioning:
1 - tank with regeneration solution; 2 - Na-cation exchanger; 3 - storage tank for SRS; 4 - SRS feed pump; 5 - conditioning unit.

At the end of the working cycle of the Na-cation exchanger 2, the process of regeneration starts, beginning with pressing the resin up to the inert media with the ascending stream of water.

After the ion exchange layer has been clamped, a regeneration solution is fed through the bottom distributors so that the ion exchange resin remains pressed upwards. 8% solution of NaCl is used. Solution is prepared and stored in the tank of regeneration solution 1. With the help of pumps, NaCl solution is fed into the water softening filter, after which all the washing water and part of the SRS are directed to the sewage system, and the greater part the actual SRS from the regeneration stage (60 m³), as described earlier, is passed into the storage tank 3. At this stage, the SRS composition is averaged before further conditioning.

Then, with the help of SRS pump 4, solution is supplied to the SRS conditioning unit 5, which includes PPC filter, high pressure pump and pressure vessels rack with membrane elements.

Permeate is sent to a tank with regenerative solution 1 for saturation with NaCl to the required concentration and then is used in the next regeneration operation. Concentrate is sent to the sewage.

Thus, the proposed scheme of SRS conditioning allows to reuse a large part of NaCl and reduces the discharge of salts and volumes of highly mineralized regeneration effluents to sewage.

3.6. Estimation of economic and environmental benefits of proposed technology

To estimate the environmental efficiency and economic feasibility of the proposed technology of conditioning of SRS from Na-cation exchanger, the material balances and efficiencies of proposed scheme were calculated.

Table 14 shows the reduction of NaCl achievable by installation of SRS conditioning technology.

Table 15 shows the reductions in the discharge of highly mineralized effluents, in particular, NaCl, due to the installation of SRS conditioning technology.
**Table 14. Reduction of NaCl consumption due to the use of SRS conditioning technology**

| Parameter                        | Plants                                    | Expenses reduction |
|----------------------------------|-------------------------------------------|--------------------|
|                                  | Existing technology | With SRS conditioning | Δ, units | R, % |
| Usage of salt for 1 regeneration, t | 2.500                      | 1.484                     | 1.016   | 40.6 |
| Consumption per year, t          | 730                          | 433                        | 297     |      |

**Table 15. Reduction of NaCl discharges and volume of highly mineralized effluents when using SRS conditioning technology**

| Parameter                                   | Plants                                    | Expenses reduction |
|----------------------------------------------|-------------------------------------------|--------------------|
|                                              | Existing technology | With SRS conditioning | Δ, units | R, % |
| Total volume of wastewater, m³              | 210                                       | 175.7                     | 34.3    | 16.3 |
| Wastewater volume per year, m³              | 17 520                                    | 7 504                     | 10 016  | 57.2 |
| NaCl discharge per 1 regeneration, t        | 1.396                                     | 0.380                     | 1.016   | 72.8 |
| NaCl discharge per year, t                  | 407.6                                     | 111                        | 297     |      |

Finally, economic efficiency of proposed technology could be estimated. Main parameters expressing the benefits from installation of the proposed conditioning plant are obtained annual savings as absolute value of economic efficiency and payback period as expression of time required for installation of proposed technology to become beneficial. Calculations are shown in table 16.

**Table 16. Savings by environmental payments achieved with installation of SRS conditioning technology**

| Parameter                                      | Plants                                    |
|-----------------------------------------------|-------------------------------------------|
|                                              | Existing technology | With SRS conditioning |
| Excess of concentration:                     | 10.8                        | 6.3                      |
| for TDS (limit 1000 ppm)                      | 30.1                        | 18.7                     |
| for chlorides (limit 240 ppm)                | 358.2                       | 299.7                    |
| Payments per 1 regeneration discharge, $      | 104588                      | 87506                    |
| Annual payments (292 regenerations), $        | —                           | 17083                    |
| Annual savings on environmental payments, $   | —                           | 54180                    |
| Capital expenses, $                           | —                           | 4026                     |
| Annual operational expenses, $                | —                           | 23128                    |
| Payback period, months                        | —                           | 16                       |
4. Conclusions

Pilot unit was developed for the study of the process of nanofiltration conditioning of the spent regeneration solution from the Na-cation-exchange water softener plant. As a result of investigation, composition of the averaged spent regeneration solution of the industrial sodium-cation exchanger filter with the UPCORE regeneration technology, operating at PP-5 in Kyiv, was determined and composition of the model solution for membrane tests was developed. As a result of a comparative study of various types of nanofiltration membrane elements it has been shown that the most effective one is DuPont (Dow) Filmtec Fortilife XC-N membrane element.

The optimal conditions for the use of the DuPont (Dow) Filmtec Fortilife XC-N membrane element for conditioning of the spent regenerative solution (temperature 23-27° C, pressure 23-25 bar, recovery 55-60%) were estimated that allowed to achieve purity of NaCl in permeate over 90% and productivity by NaCl of 13.1 kg/h.

Technological scheme of the process of nanofiltration conditioning of the spent regeneration solution, based on the use of the DuPont (Dow) Filmtec Fortilife XC-N membrane elements, has been developed, the application of which will allow to achieve a reduction of NaCl consumption by 40% for the regeneration process, and a 72% reduction of NaCl discharge into sewage.

Economic efficiency of proposed technology could be expressed by achieving more than $23000 of annual savings on NaCl together with $17000 of annual savings on environmental payments that allows to achieve payback period on 16 months.

References

1. Global salt production, 2020 | Statista. https://www.statista.com/statistics/237162/worldwide-salt-production/ (accessed Feb, 2021).

2. Ion exchange regeneration methods, http://dardel.info/IX/processes/regeneration.html (accessed Sep, 2021).

3. New Zealand Institute of Chemistry article entitled “Ion Exchange Resins” by David Alchin (Service Chemist, Drew New Zealand) with summary by Heather Wansbrough at http://nzic.org.nz/ChemProcesses/water/13D.pdf - pg. 7, 2016.

4. Grasso, D. et al. J. of Environmental Systems, 1992, 22(4), 297.

5. Water Softeners and Septic Systems | Fine Homebuilding, https://www.finehomebuilding.com/forum/water-softeners-and-septic-systems (accessed May, 2008).

6. Kozlov, P. V. Development of low-waste and resource-saving technology of water softening. Doctoral candidate's thesis, Igor Sikorsky Kyiv Polytechnic Institute, Ukraine, 2009.

7. Brigano, F. A.; Soucie, W. J.; Rak, S. F. Reclaiming of spent brine, US Patent 5254257A, January 19, 1993.

8. On Drinking Water and Drinking Water Supply. Legislation of Ukraine, https://zakon.rada.gov.ua/laws/show/2918-14#Text (accessed May, 2017).
ЕКОНОМІЧНІ ТА ЕКОЛОГІЧНІ ПЕРЕВАГИ ПОВТОРНОГО ВИКОРИСТАННЯ РОЗЧИНУ NaCl ЗА ДОПОМОГОЮ НОВОЇ МЕМБРАННОЇ ТЕХНОЛОГІЇ

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Катіонообмінне пом'якшення води є однією з найбільш широко використовуваних технологій водопідготовки. Однак її вплив на навколишнє середовище, пов'язаний зі скиданням висококонцентрованого регенераційного розсолу, привертає все більше уваги через зниження загальної якості та доступності водних ресурсів. З огляду на високий вміст у скидуваному розсолі NaCl, який можна повторно використати, необхідна технологія, яка дозволить знизити вплив на навколишнє середовище і допоможе повторно використовувати розсіл.

Для розробки такої технології було досліджено склад відпрацьованого розсолу розчину з Na-катіонообмінного фільтра і проведено кондиціювання цього розчину з використанням нанофільтраційних мембран різних типів за різних температур, тиску і ступеня вилучення. Результати показали, що оптимальними умовами для регенерації NaCl є використання мембранних елементів DuPont (Dow) Filmtec Fortilife XC-N при температурі 23-27° C, тиску 23-25 бар і регенерації 55-60 %. У цих умовах досягнута чистота NaCl в пермеаті більше 90%, продуктивність по NaCl склала 13,1 кг/год. Запропоновано принципову технологічну схему процесу мембранного кондиціонування відпрацьованого регенераційного розчину, що дозволяє знизити витрати NaCl на 40 % і зменшити скидання NaCl в стічні води на 72 % з відповідними економічними та екологічними вигодами.

Ключові слова: мембранна технологія, пом'якшення, розсіл, хлорид натрію, нанофільтрація.