On the choice of the water treatment technology for rural areas

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Abstract. Most water supply systems in rural areas of the Russian Federation were built in the last century. At the same time, no more than 18% of consumers of small settlements are provided with drinking-quality water. The rest of the population living in rural areas has to use untreated underground and surface water which does not meet sanitary-chemical (40.3%) and microbiological (35.5%) indicators. Most of such water supply sources are exposed to anthropogenic and technological environmental impact with varying degrees of intensity. Intensive deterioration in the natural waters quality, the absence of water purification and waste water treatment plants in rural settlements and villages significantly increases the risk of emergency situations occurrence associated with mass infection of the population with waterborne pathogens. One of the ways to provide the villagers with high-quality drinking water is through modular water treatment plants of various capacities. This work presents the first part of development research of the water treatment and disinfection technology carried out in laboratory conditions. The proposed technology allows treatment of natural water to the SanPiN 2.1.4.1074-01 quality without use of imported reagents and the permanent presence of maintenance staff.

1. Introduction
The Russian Federation (RF) is ranked second in the world by natural water reserves in the world [1]. Over 2.5 million of large and small rivers flow through the territory of Russia, while in many regions of the country there is a shortage of drinking water due to the extremely uneven distribution of water resources and a high degree of their pollution, especially in the Southern Federal District (SFD) [2].

The SFD surface waters analysis indicates their unsatisfactory quality in the most developed sections of the rivers – the Don, the Volga, the Kuban, etc. The waters of these rivers are classified as polluted, dirty and extremely dirty; they cannot be used for drinking purposes without treatment [1,3,4]. Thus, according to [1], the Lower Don water quality (from the Tsimlyansk city to the Azov city) belongs to class 4 “A” and is assessed as “dirty”. Such water does not correspond to sanitary-chemical (40.3%) and microbiological (35.5%) indicators [1].

In connection with the intensive anthropogenic and technological environmental pollution of surface waters, underground sources are of increasing interest for water supply in rural areas [5-8]. For drinking and household purposes up to 70% of the rural population in the Russian Federation has to...
use water from underground sources without treatment [1-6,9-12]. According to the data of [1-4], centralized sewerage systems are absent in many rural settlements, as well as in a number of small towns and villages with extensive individual residential development. The resulting wastewater is discharged without treatment into cesspools, which affects the quality of underground and infrabed water. In the Southern Federal District there are operated about 3,600 water pipelines which, according to existing estimates, are in the second and third groups of sanitary and epidemiological welfare, and this is qualified as unsatisfactory janitorial condition [1,2,13]. And also, one cannot ignore the fact that many people refuse from the alternative drinking – bottled water, preferring to use their own sources, which most often are undrinkable [14].

Intensive deterioration in the natural waters quality, the absence of water purification and waste water treatment plants in rural settlements and villages significantly increases the risk of emergency situations occurrence associated with mass infection of the population with waterborne pathogens [10,15,16]. To develop a technology that allows the natural water treatment with minimal investment expenditures and operational costs we have studied existing technologies.

Operated water treatment plants are most often based on laborious and cumbersome water treatment technologies (reagent and chlorination facilities, vertical or horizontal sedimentation tanks, high-rate or low-rate trickling filters, etc.) [14,17-20]. Such technologies require significant labor contribution, the availability of qualified maintenance staff, and also they directly depend on the supply of reagents.

Small-sized water treatment plants of various manufacturers are widely known in the domestic market [18,19]. Thus, the Ministry of Emergency Situations is armed with mobile filter plants on the automobile base of the MAFS-3; VFS-2.5; VFS-10 and SKO-10 “Hygiene” types [21-23]. The main disadvantages of such plants are the short (not more than 4 days) running time with the stock of reagents; disinfection with ultraviolet radiation (this method does not provide a prolonged effect of bactericidal water treatment); the use of expensive membrane technology.

To reduce the area occupied by chemical feed plants, as well as the costs associated with their delivery, it is necessary to apply a different method of the coagulant introducing into the treated water. One of such methods is the electrochemical coagulation (ECC), which for a long time has attracted the attention of researchers due to its high efficiency, ease of technological parameters regulation and compactness [24-26]. The ECC use makes it possible to abandon the use of the imported coagulant when replacing it with an aluminum electrode, which forms a coagulant at the electrochemical dissolution.

In the case of electrochemical dissolution of the anode, which can be installed in close proximity to the surface of the filtering layer, it is possible to implement the contact coagulation process. Filtering is the next technological stage of water purification after coagulation.

The final stage before water is supplied to the population is its disinfection. The analysis of existing methods of water chlorination shows that from the point of view of safety and efficiency of use, it is reasonable to use the electrolytic production of sodium hypochlorite solution directly at the place of its consumption from natural waters [27,28]. This will simplify the operation of the plant, increase its reliability, and in addition, to entirely automatize the technological process.

In such a way the electrochemical dissolution of aluminum anodes, contact filtering and chlorides oxidation can be realized, which provides clarification, discoloration and disinfection of water.

Experimental part

This work presents the development research of the water treatment and disinfection technology, carried out in laboratory conditions with natural Don water (Table 1) at the installation shown in Figure 1. The plant consisted of flow-through electrolyzers (3) and (13) for primary and secondary disinfection respectively, a filtering column (6) with an integrated electrocoagulator (7).

The Don water was examined at the water and wastewater treatment facilities of the municipal unitary enterprise “Gorvodokanal” in Novocherkask. From the presented data (Table 1) it can be seen that the water quality does not correspond to the drinking and household purposes upon indications of
turbidity, colority, permanganate oxidizability (PO), total microbial count, total coliform bacteria (TCB) and thermotolerant coliform bacteria (TtCB).

Table 1. The main indicators of the examined Don water in the last five years.

| Water quality indicator | Requirement criterion according to SanPiN 2.1.4.1074-01 | Examined water indicators |
|-------------------------|------------------------------------------------------------|---------------------------|
| Colority, degree        | 20.0                                                       | 6.9–24.6                  |
| Turbidity, mg/dm³       | 1.5                                                        | 0.8–29.0                  |
| pH, pH units            | 6.00–9.0                                                   | 7.8–8.8                   |
| Dry residue, mg/dm³     | 1000.0                                                     | 979.0–534.0               |
| Detection limits, mg/dm³| 5.0                                                        | 3.8–5.5                   |
| Total hardness, mg-eq/dm³| 7.0                                                        | 4.9–6.9                   |
| Total iron, mg/dm³      | 0.3                                                        | 0.1–0.15                  |
| Chlorides, mg/dm³       | 350.0                                                      | 117.0–150.0               |
| TtCB, CFU in 100 ml     | None                                                       | 13.0–99.0                 |
| TCB, CFU in 100 ml      | None                                                       | 32.0–588.0                |
| Total microbial count, CFU in 1 ml | no more than 50.0                                   | 50.0–830.0                |

The filtering column (6) was made of transparent plastic. The total height of the column is 2.4 m, the inner dimension area is 0.1 m². ODM-2F (shattered modified molding box) was used as the upper filtering layer (10), with the grain size of 2.3 - 3.5 mm and the height of 700 mm. The substratum is the quartz sand (11) with the grain size of 0.7 - 1.5 mm and the layer height of 700 mm. The column was rinsed with the tap water in the bottom to top direction (14) with the intensity of 10 l/s • m² for 6 minutes. The flow rate of the treated water was 1 m³/h.

The electrocoagulator (7) was made of 11 aluminum electrodes (type AD1). The plates size was 145 × 145 × 6 mm, the distance between the electrodes was 3 mm. A voltage of 7-20 V was applied to the electrocoagulator. The current density varied from 10 to 80 A/m². The electric current polarity reversal at the electrocoagulator was used every 15 minutes.

Two identical flow-through electrolyzers (3) and (13) with overall dimensions of 1400 (L) × 160 (D) mm, operated on power supplies with the possibility of polarity reversal and the current strength control, were used in the research. The current strength varied from 5 to 20 A at a pitch of 5 A, which corresponded to the current density of 25-100 A/m². The oxide iridium-ruthenium-titanium anode (OIRTA) with the mass ratio of iridium to ruthenium 80:20; 50:50 and 0:100 with the specific filling of precious metals of 7.5 g/m² was used as the electrode. In each test the running time of the plant was 10 hours.

For the protection from deposits formed on the electrolyzer cathodes the electric current reversal method was chosen. The electrolytic process was carried out for 60 minutes without the reverse, followed by the change in polarity in the range from 25 to 300 seconds.

In the ECC and CF experiments the main technological indicators were examined – the time of the protective action of the filtering layer and the dynamics of the increase in head loss in the filter media using the piezometer (16). For the comparative analysis of the ECC efficiency parallel experiments were carried out using reagents: aluminum sulfate (AS), aluminum oxychloride “Aqua-Aurat™30” and coagulant with enhanced flocculant property “SKIF™180”. The solution was supplied using the dosing pump (18) from the solution tank (17). In the research the reagents doses were ranged from 5 to 11 mg/dm³ of Al₂O₃. The temperature of the examined water was in the range of 10 – 17°C.

The research was carried out in two stages. At the first stage we studied the features of the active chlorine production from natural water chlorides, the nature of the deposits formation on the electrodes depending on the current density, as well as the effect of the electrode coating material on the electrolytic process. At the second stage the electrochemical coagulation was examined. The anodic current density was determined to obtain the optimal dose of aluminum for the Don water treatment. The main technological parameters for the joint operation of the electrochemical coagulator
and the contact filter were determined. Active chlorine, residual aluminum, colority, turbidity, and pH were monitored in the treated water during the research.

![Figure 1](image)

Figure 1. Scheme (a) and photo (b) of the laboratory plant: 1 - supply of source water to the plant; 2 - control valve; 3 - flow-through electrolyzer (primary disinfection); 4 - flow meter; 5 - scattering watering can; 6 - filtering column; 7 - electrocoagulator; 8 - sampler; 9 - rinsing water drainage; 10 - upper layer (ODM-2F); 11 - substratum (the quartz sand); 12 - filtrate drainage; 13 - flow-through electrolyzer (secondary disinfection); 14 - water supply for rinsing; 15 - gas outlet; 16 - piezometer; 17 - tank for reagent solution; 18 - dosing pump; 19 - control valve.

The following presents the results of the first research stage. Since the electrolyzers of the primary and secondary disinfection were the same, all studies to determine the technological parameters of direct Don water electrolytic process were carried out on the electrolyzer (item 3, Fig. 1).

2. Experimental results

Figure 2 shows the dependence of the active chlorine concentration on the anode current density. With an increase in the current density by 4 times, the concentration of active chlorine in the treated water increased by 9 times and reached 31.28 mg/dm³; such an increase in concentration is explained by the large amount of electricity passed through the solution, which, in accordance with the Faraday’s law, contributes to the formation of a larger active chlorine amount.

![Figure 2](image)

Figure 2. The effect of the anode current density on the active chlorine concentration during direct Don water electrolytic process.

For the qualitative assessment of the direct electrolytic process the dependence of the chlorine current yield on the current density was built (Figure 3). The chlorine current yield did not exceed 16%, which, given the rather low concentration of chlorides in the Don water (117 - 150 mg/dm³), can be considered as a good result. The increase in the current density from 25 to 100 A/m² increased the chlorine current yield by 8%. Further research was carried out with the current density of 100 A/m².
Figure 3. The effect of the anode current density on the chlorine current yield during the direct electrolytic process of the Don water.

At the direct electrolytic disinfection of water, not only a reasonable choice of anode coating material is necessary for the efficient electrolyzer operation, but also the observance of optimal electrophysical process parameters (anode current density, electrolyte consumption, measures to prevent hardness salts deposition on the cathode) corresponding to a specific water composition. The easiest way to prevent the hardness salts deposition during the direct electrolytic process is the increased flow rate of water in the electrolyzer (0.1-0.3 m/s), combined with the polarity reversal (reverse) – periodic switching of the electrode operating mode from the “+” anode polarization to the cathode “-” and vice versa.

Figure 4 shows the effect of current reverse on the active chlorine concentration and the amount of deposits on the electrodes surfaces. Each test was carried out for 100 hours. It follows from figure 4 that at the electrolyzer operation with the current reverse (experiment 6) the active chlorine concentration was 38% higher than at the electrolytic process without the current reverse. Simultaneously during the research, the cathode deposits amount was monitored. It can be seen that at the operation mode of the electrolyzer (τ− – 1 h, τ+ – 300 sec), the weight of deposits decreased by 90 times compared with the experiment without the current reverse and was equal to 0.009 g.

Figure 4. The effect of the current reverse on the amount of deposits formed on the cathode surface and the active chlorine concentration: 1 – without reverse; 2 - (τ− – 1 h, τ+ – 25 sec); 3 - (τ− – 1 h, τ+ – 60 sec); 4 - (τ− – 1 h, τ+ – 120 s); 5 - (τ− – 1 h, τ+ – 210 s); 6 - (τ− – 1 h, τ+ – 300 sec).

It is known that current reverse contributes to the achievement of more economical electrolytic process parameters. The increase in the time interval for changing the electrodes polarity makes it possible to accumulate deposits at the cathode, which slows down the electrochemical reduction of sodium hypochlorite at the cathode and increases the chlorine current yield. At the reverse (test 2), the chlorine yield increased by 3.2% in comparison with the test 1. With the increase in the reverse time to 300 seconds (test 6), the chlorine yield increased by 5% relative to the test 1 and reached 13.3%.
As known, the electrode material and the composition of its coating exert a significant impact on the electrolytic process efficiency and the operational life of the electrodes. Therefore, to select the composition of the anode coating, experiments were conducted on anodes with different mass ratios of iridium to ruthenium: 80:20; 50:50 and 0: 100 (Figure 5).

Figure 5 shows that the increase in the mass of iridium in the coating increases the concentration of the resulting active chlorine. The increase in the active chlorine concentration with the increase in the Ir proportion to 80% was 20.5%. Also, the presence of iridium significantly affects the operational life of the electrodes. The curve \( \tau_{\text{ж}} \) shows that the presence of Ru in the oxide layer in a mass ratio to Ir (20/80) increases the anode operational life by a factor of 10.

At the second stage of the research the parameters of the joint operation of the electrochemical coagulator and the contact filter were determined. The aluminum anode activity largely depends on the nature and concentration of the anion present in the solution. Of all anions, the greatest effect on the activity of the aluminum anode is made by the chloride ion. The aluminum anode activation by chloride ions is also explained by the strong deceleration of the oxide film formation process associated with the adsorption displacement of oxygen [26].

According to the proposed process flowsheet, the first stage provides for the electrolytic process of natural water for primary chlorination (Figure 1). Thus, the phenomenon of the aluminum anode depassivation by the chloride ions present in the examined water, together with the reverse interval of 15 minutes, will ensure the optimal operation of the electrodes at the ECC.

The research (Figure 6) showed that the increase in current density from 2 to 8 mA/cm\(^2\) is accompanied by the increase in metal yield by 12%. Figure 6 shows that the increase in the density of the anode current from 2 to 4 mA/cm\(^2\) results in the increase in the aluminum yield by 7%, then a gradual increase in the metal yield by 2 and 3% for current densities of 6 and 8 mA/cm\(^2\), respectively, is observed. The further increase in current density results in the high content of residual aluminum in the treated water. The obtained results concerning the effect of current density on aluminum yield found good agreement with the data of [25,26], in which a similar qualitative dependence between current density and aluminum yield was found.
Figure 7 shows the dependences of turbidity \((a)\) and colority \((b)\) in filtered water with addition of various reagents. Figure 7\(a\) shows that the effect of the Don water turbidity reducing after its treatment using “SKIF™180” and the ECC was more than 90 - 95% at doses of 3-4 mg/dm\(^3\). While for “Aqua-Aurat™30” and AS, the clarification effect is 80 - 85%, the doses are 5 and 9 mg/dm\(^3\), respectively.

From a comparison of the data shown in Figure 7\(b\), it can be seen that “SKIF™180” proved to be the best coagulant at the dose of 5 mg/dm\(^3\) the effect was 65.7%. The ECC and “Aqua-Aurat™30” at the same Al\(_2\)O\(_3\) values reached 55%.

![Figure 7. Change in turbidity \((a)\) and colority \((b)\) of water during its coagulation treatment depending on the reagent dose and the coagulant nature: 1 – AS; 2 - Aqua-Aurat™30; 3- SKIF™180; 4 – ECC; 5 - Requirement SanPiN 2.1.4.1074-01.](image)

Also in the research the main technological indicators characterizing the effectiveness of the joint operation of the ECC and contact coagulation were observed. The filtering rate and the head loss in the filter media (every 350 mm), as well as the layer-by-layer change in treated water turbidity in the filter media and at the inlet and outlet of it, were taken as control parameters. The experimental results are presented in the form of graphical dependencies (Figures 8 and 9).

From Figure 8 it can be seen that in the upper layer of ODM-2F equal to 350 mm, the ratio of the suspended materials concentration in the filtrate \((C)\) to the initial Don water turbidity \((C_0)\) was 0.67. At the end of the filter cycle, the residual turbidity \((1)\) was 7 mg/dm\(^3\) with its initial value of 10.5 mg/dm\(^3\).

Indicators of filtered water \((4)\) after long-term operation of the plant (24 hours) were compliant with the sanitary standards – 0.93 mg/dm\(^3\).

When studying CF at the pilot plant, the turbidity of the filtrate and water taken through samplers in the layers of the filter media was determined. The upper layer of ODM-2F collects the bulk of the contaminants – about 50%, the lower part of the ODM-2F filter media – about 33%. Quartz sand collects about 12% of the remaining particles.

In the graph of the head loss change depending on the running time of the filter plant (Figure 9), there are two peculiar sections: from 0 to 8 hours there is a uniform increase in head loss to 0.4 m; in the section from 8 to 24 hours the head losses vary unevenly, increase, and then decrease. This is due to the fact that during the water ECC process electrolytic gases are released; they penetrate into the filter media with the treated water stream, which entails the formation of air “pockets” in the filter media layers.
3. Conclusion

The results of the research conducted showed the high efficiency of using the combined processes of the ECC and CF at the Don water treatment (table 2). The proposed technology allows treatment of natural water to the SanPiN 2.1.4.1074-01 quality without use of imported reagents and the permanent presence of maintenance staff.

It was found that the optimal dose of the electrochemical coagulant of 2–3 mg/dm³ for Al₂O₃ is achieved at the current density of 40 A/m². Taking into account the necessary effect of the water clarification discoloration and disinfection, as well as the residual aluminum concentration, the optimal current density is 1.5 - 4 mA/cm². The filter cycle time is 10 hours with an initial turbidity of 9.0-12.2 mg/dm³. The main technological parameters of direct Don water electrolytic process were determined: the current density is 100 A/m², the anodic coating composition is OIRTA (Ru/Ir – 20/80), reverse mode (polarity reversal) τ⁻ – 1 h, τ⁺ – 300 sec, chlorine current yield is 14%.

The results of the presented laboratory research were used in further production tests of the proposed technology and will be published in the nearest time.

| Water Qualitative Indicators | Source Don Water Quality | Plant Operation Time |
|------------------------------|--------------------------|----------------------|
|                              | 2 h | 4 h | 6 h | 10 h |
| Turbidity, mg/dm³            | 12.2 | 0.34 | 0.42 | 0.50 | 0.62 |
| Colority, degree             | 16.6 | 4.2 | 4.6 | 4.9 | 5.2 |
| pH, pH units                 | 7.9 | 8.1 | 8.1 | 8.1 | 8.1 |
| Residual active chlorine, mg/dm³ | - | 0.8 | 0.76 | 0.79 | 0.79 |
| Residual aluminum, mg/dm³    | < 0.04 | 0.08 | 0.08 | 0.08 | 0.08 |
| Total microbial count, CFU in 1 ml | 240 | 7 | 8 | 8 | 9 |

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