Modern water treatment system for high-quality water used in the energy industry

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Abstract. This article provides the detailed optimization processes and enhancement, in the field of water treatment systems, for the energy sector needs. The developing of the unique water purification system design based on modern techniques for equipment is presented according to ASTM standards. As well as the project proposes a new methodology for complex analysis of quality data after each purification section in order to manage all possible need in the water for the power plant. The analysis allows producing the more accurate selection of the filter systems, thereby prevent failures of such sophisticated and expensive equipment as reverse osmosis and continuous electrodeionization.

Introduction

The main purposes of introducing optimization processes and enhancement in the field of water treatment systems (WTS) for the energy sector needs [1] is a prevention of corrosion and boilers deterioration [2, 3] thus ensuring an increase of power units efficiency and protection of components, minimization of blowdown and reduction in the use of chemical reagents. The building scheme of the WTS is the general plan, which contains the full project definitions (as requirements program, treatment scheme, phasing of construction, estimation of an investment cost) and also is important for international decisions, including such considerations as the project mandate for organizational, technical, contractual and financial aspect. [1, 4] Improving energy efficiency in the WTS allows reducing total demand, avoiding the risk of brownouts or blackouts during high energy demand periods. Water efficiency strategies reduce the risk of water shortages, helping to ensure a reliable and continuous water supply. [4, 5]

At the current moment, widescale projects for the implementation of new high-tech combined cycle gas turbine (CCGT) plants implement in the power systems of the Russian Federation. In this regard, the requirements for the boiler feed water of the steam-turbine unit also increase: instead of the previously demanded electrical conductivity of the feed water for supercritical power units less than 0.3 μS/cm, combined-cycle power units put forward a requirement with an electrical conductivity of less than 0.2 μS/cm. [6]
Traditionally, for ensuring a quality of the boiler feed water simplified water treatment is used, for instance, Raw water reservoir - Dry filtration – Rapid bulk filtration - Adsorption - Softening - UV-disinfection – Microfiltration - Clear water reservoir. [1, 7, 8] However, increased requirements for desalinated filtrate will cause a decrease in a filter run that finally will lead to increase in operational expenses and decrease in reliability of plant operation.

Firstly, the ultra-pure water related to the electronics and microelectronics industries. The system developed within the framework of this project is aimed at providing all kinds of water consumption on the power plant, not only needs in the feed water, but maintenance of component parts of power units and electronic components by this reduce the total investment cost. The limits on the impurities are related to current contamination specifications were obtained by analytical methods (these processes are described in part 3), laboratory or on-line instrumentation control are also envisaged in building design (see part 2) and are used in accordance with current industry practice. The stage for water selection is defined in accordance with the specific manufacturing process and the water-quality recommendations apply at the point of distribution.

There are several international professional organizations that set technical standards for the quality of ultrapure water: International Organization for Standardization, American Society of Testing Materials, Semiconductor Equipment and Materials Institute, etc. In general, these organizations specify four types of water with three additional degrees of purity, described in the normative document requirements for deionized water. For a long time in Russia, the requirements for ultrapure water are regulated by OST 11.029.003-80. However, due to large-scale changes in the energy and electronics industries over the past decades, these requirements for the quality of de-ionized water are considered obsolete. Increasingly, engineers of modern Russian water treatment companies in the design of purification systems are guided by the standard ASTM D5127-13 «Standard Guide for Ultra-Pure Water Used in the Electronics and Semiconductor Industries». [9].

Development of the treatment scheme of WTS

The treatment scheme is embedded in the general planning process, first of all, is based on the data on the quality of raw water, requirements for purification water and requested process flow diagrams (PDF) of water consumption. Comparison of the laboratory analysis of initial water to requirements is a prime preparatory design stage of the station of water treatment. This project proposes a unique system of complex calculation and analysis of quality data for all purification sections in order to manage different needs described in part 1. Application of this way of technological development allows specifying most necessary and enough an inventory thanks to what it is possible to reduce overall dimensions of the station of water treatment and to considerably reduce prime cost of the project [1, 8].

In the presented article, we consider the full technological process of the ultra-pure WTS for the nuclear power station needs. The raw water source is the system of the central water supply. The treatment scheme comprising PDF is based on laboratory control data according to requirements of the ASTM D-5127-13 to type E-1 and is represented in Figure 1.

The primary section of the WTS utilizes the pretreatment and desalination processes. The purified water at the first stage passes a mesh water filter (MF) with the spectrum of filtration ranges of 100 µm. The water produced in the primary section has a purity equivalent to Type E-4 and is stored prior to use or next additional purification.

The secondary purification section is dedicated to bringing the effluent of the primary section up to the purity level of Type E-3. This section includes removal of organic and biological material and as well as includes additional desalination processes. This section includes removal of organic and biological material, with sand as a foundation in all cases, and as well as includes additional desalination processes:

- inorganic particle removing filters (FF), principally Fe (regenerative);
- adsorption filters (AF) with the activated carbon for chlorine, its derivatives and organic impurities removing(regenerative).
- water softening by two-bed ion-exchange filters (SF) with synthetic materials (NaCl for a regeneration).

Water treatment by the adsorption method was widely adopted in the production of water treatment and also processes of receiving valuable components of waste products. [10] Additionally, ultrafine particulate removal is implied in this treatment section. A significant part of the clear water flow from this section goes to energy production department (where be used as feed water) directly thus a degradation of the resistivity is avoided.

Figure 1. The scheme of the ultra-pure water treatment

Tertiary filtration or final removal process increases the purity to the requirements of type E-2 or E-1. This section includes ultraviolet light (UV) (254 nm), reverse osmosis, continuous electrodeionization and mixed-bed ion-exchange filters (MIF). The water from the tertiary section of the system is used with increased requirements for storage and is recirculated continuously (will be described in part 4).

Experience with ultraviolet radiation shows that if the dose of actual irradiation is not lower than a certain value for a particular water quality, then a sustainable decontamination effect is guaranteed. In the world practice, the minimum radiation dose requirements range from 16 to 40 mJ/cm². Removal of biological and organic contaminants is an important adjunct to any system used to prepare ultra-pure water. Dissolved organic compounds can accumulate in the system during the process as well as being present in the original water. Ultraviolet irradiation at 254 nm significantly reduces the growth of organisms by dislocating the DNA base pairs. This process prevents the bacteria replication, furthermore, total organic carbon (TOC) is reduced.

RO and EDI belong to the most advanced technologies in the production of ultrapure water, due to the ability to recycle some portion of the wastewater also. In presented RO system the water purification follows the next scheme: the first stage permeate goes to the second stage of RO, while
the first stage concentrate fed back into the feed water supply to be recycled through the RO system to save water; the second stage concentrate goes to drain.

In accordance with the PDF shown in Figure 1, after the RO phase, the final water purification is carried out using electrodeionization (EDI) - the process of continuous demineralization of water using ion-exchange resins, ion-selective membranes and a constant electric field. Electrodeionization modules combine the advantages of speed and efficiency of ion exchange with the absence of a laborious and dangerous for the health and environment stage of regeneration of ion-exchange resins with acid and alkali. Modern installations of electrodeionization of water make it possible to obtain water with a resistivity of 18 MOhm*cm. In the process of EDI, about 5-7% of the drainage water (concentrate) is formed, which is sent to the clean water reservoir (type E-4).

**Quality analysis of the feed water according to requirements**

The application of reverse osmosis and electrodeionization, in industrial water treatment for needs of the energy sector, is not so widespread therefore there are simplified schemes with bunk filters are used. The choice of the membrane depends upon thereof the pore size, characteristics of RO system and the size of particles to be removed. This is due to the limited life of RO membranes and the high cost of components in that the membrane surface is exposed to organic, colloidal and mechanical deposits. However, often the real reason for reducing the life of the plant and premature deterioration of membranes are design errors. [12] Accordingly conduction of a qualitative analysis of all stages of water treatment that precede reverse osmosis is a necessity, and in case of unsatisfactory water quality, use additional methods of cleaning, especially in the presence of surfactants and petroleum products. [13]

Table 1 presents the water quality indicators obtained by calculation, including using software Integrated Membranes Solutions Design Software.

**Table 1. The change in water quality after each type of treatment**

| Parameter             | Unit | Quality data of the raw water, treated water and requirements | Clear water | Requirement |
|-----------------------|------|--------------------------------------------------------------|-------------|-------------|
|                       |      | Raw water    MF   FF   AF   SF   RO*       |             |             |
| TOC                   | μg/L | 3,0          0,6  0,2  0,1 | 0,000       | < 2         |
| Turbidity             | μg/L | 0,96         0,38 0,08 0,05 | 0,000       | < 0,1       |
| Alkalinity            | mmol/L | 1,42     1,2 | 0,25 0,298*** | < 0,1       |
| Hardness              | mmol/L | 1,92     1,8  1,3  0,1 | 0,002       | < 0,02      |
| Iron                  | μg/L | 0,05         | 0,01             | 0,000       | < 0,02      |
| Manganese             | μg/L | 0,08 ± 0,02  0,03 | 0,001       | < 0,05      |
| Dissolved oxygen      | μg/L | 3,52         1,6 | 0,1 10         |             |
| Ammonium              | μg/L | 0,143        0,1 | 0,01 < 0,1     |             |
| Chloride              | μg/L | 4,66         1,2 1,5 0,000 | < 0,02     |
| Nitrate               | μg/L | 0,55         | 0,1 0,002       | < 0,05     |
| Calcium               | μg/L | 19,38        2,0 | 0,001 < 0,02    |             |
| Sulfate               | μg/L | 26,06 ± 5,21 |              | 0,001 < 0,05|             |
| Magnesium             | μg/L | 9,22         1,2 | 0,000 < 0,05    |             |
| Residue after evaporation | μg/L | 133          | 116,5 0,42   | < 0,5       |
| Sodium                | μg/L | 6,291        28,82 0,112*** | < 0,05     |
| Resistivity, 20°C     | On-line | 165** | 1,2 | 18,1         |             |
The parameters were calculated automatically in the program IMS Design Software for a two-stage RO with 12 membranes such as Hydranautics CPA2-4040 for the flow of 4.15 m³/h.

* – The value was obtained automatically in the software after input of the original data.

** – The required values are achieved by means of final filtration at the electrodeionization unit and mixed-bed demineralization filters.

**Storage and distribution systems**

The storage of high-quality water during production is very important. In proportion to the area and time of contact between the water, the air and the containment materials, the impurities penetrate into the clear water. It is necessary to provide a WTS with a loopdistribution design. Particular emphasis must be placed upon the atmosphere above the water, since those gases may contaminate the water with biological, organic, inorganic, and particulate impurities. [9]

In the considered project, high-purity nitrogen is used to blanket the atmosphere above the ultra-pure water stored in the container after deionization stage. As the distribution system presents a large area of contact between the water and pipes and biological impurities tend to accumulate in stagnant water, for those reasons, the flow of clear water is maintained on a continuous 24-h basis. To maintain the required quality E-1 additional mixed-bed ion-exchange (nonregenerative) systems is required. MIFs are shown in the treatment scheme and are a part of the loopdistribution.

**Conclusion**

Summarizing the issues and results discussed in the provided article:

- The unique water treatment scheme provides all kinds of water consumption on the power plant, as the feed water, high-quality water for the maintenance of component parts and electronic components of power units were developed and presented in Figure 1.
- By this design, there is the total investment cost of WTS for the plant, in general, is reduced.
- The changes in the main water quality indicators were determined after each stage, that allows determining a water take-off location for specific needs and simplifies the on-line instrumentation control, the results are presented in Table 1.
- The loopdistribution design and recycle system were envisaged as well.

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