Wastewater treatment and application in the advanced nanofiltration system

I R Junussova1, S V Chicherin2

1Non-profit JSC Almaty University of Power Engineering and Telecommunications, Kazakhstan
2Omsk State Transport University, Russia

E-mail: man_csv@hotmail.com

Abstract. The Aral Sea Region is characterized by being a very demanding consumer of industrial wastewater treatment. We studied the effects of various pretreatment methods on aluminum production. This method can be used as an alternative one in industrial wastewater treatment. The aim of multi-year study is to explore a nanofiltration as a one of the most attractive technologies for this application since nanofiltration membranes can retain ions and small organic molecules from an aqueous solution. But it is also very challenging due to the presence of salts and operating problems such as fouling, salt deposition, etc. Result becomes available thank to experimental set-up based on an ion exchange and a reverse osmosis. Results are also verified by evaluation tests and field applications showing their usage and wastewater conversion efficiency. The technological scheme includes combined water treatment plant using desalination technology and additional block functioning for an aluminum production and a temporary storage. Aluminum is to be produced of the Syr Darya river rich of it with the help of cutting-edge technology of oxide film removal and cartridge packing. This work evaluates the use of aluminum accumulated in the reaction unit by means of aluminum powder plus water module to reduce the pollutant contents of industrial wastewater quickly and effectively. The invention makes it possible to reduce the cost of aluminum by 3-4 times. Energy consumption of the desalination process was also discussed. Extracted aluminum is a superior material for industry. The high activity of aluminum to water is prohibited by a thin layer of aluminum oxide on its surface. The water treatment system with a combined phase purification and desalination may contribute up to 50 per cent to meeting the reduction of energy consumption for end product (aluminum).

1. Introduction
One of the major industry directions is escalating capacities requiring new sources of energy and fresh water. Integrated management within the Aral Sea region is needed to help balance competing uses of water resources of Syr Darya river. It is polluted by waste water rich of aluminum salts from processes where aluminum compounds are used as catalysts for the metathesis polymerization or ethylbenzene production. Aluminum and its alloys are widely utilized in the different industries thanks to the solid oxide film on the surface leading to high corrosion resistance.

Abdel-Fatah [1] also shows the potential and place of wastewater treatment in future water supply systems, if adapted to involve renewable energy sources for cost-effective fresh water generation and distribution. Several studies [2-6] looked at waste water sludge, and found it potentially appropriate to produce aluminum although it would require significant technological improvement. Pal et al. [7]
specifically drew a connection to the transfer of learning from simulation experience through examining the model of combining treatment and recirculation of leather industry wastewater. None of the proposed projects considered designing a facility able to generate aluminum and fresh water at the same time.

2. Materials and methods

Technological layout of the experimental facility based on water treatment and reversed electrodialysis units is shown in figure 1.

Figure 1. The technological scheme of the designed compound water treatment plant: 1 – Well, 2 – Storage tank, 3, 5 – Centrifugal pump, 4 – Pretreatment consists of an ultrafiltration module, 6 – Reaction unit for extracting aluminum from water to produce hydrogen, 7 – Supply line of treated water to consumers.

To extract aluminum from the concentrated waste water and make water usable directly by people, animals and plants pretreatment of desalination plants by pressure driven membrane processes (microfiltration, ultrafiltration and nanofiltration) considered to be preferred (fig. 1, position 4).

Reusing $K_{ru}$, waste treatment $K_t$ and recycling $K_{rc}$ indexes are applicable to analyze waste water usability. Values of indexes varies from minimum to maximum levels.

$$K_{ru} = K_t \cdot K_{rc}$$  (1)

Reusing index $K_{ru}$ evaluates the quality of process from the economic point of view. Waste treatment index $K_t$ characterizes the share of collected waste water and recycling index $K_{rc}$ is used to understand the amount of recycled waste water that can be reused later [8].

The description of the experimental facility is given in table 1.

| Module type and its characteristics | Ultrafiltration module | Multi-stage electrodialysis module |
|-------------------------------------|------------------------|-----------------------------------|
| Water capacity, dm³/h               | 100                    | 100                               |
| Salinity of original waste water, mg/dm³ | 4579.0               | 6.0..3.0                          |
| Salinity of fresh water, mg/dm³     | 6.0..3.0               | 0.5..1.0                          |
| Number of cell membrane, pcs        | 6                      | 80                                |
| Voltage between the electrodes, V   | -                      | 110..180                          |
| Mass of a plant when injector chamber is filled with water, kg | 35                     | 20                                |
| External dimensions, mm             | 330x330x450            | 330x330x450                       |
| Electricity consumption, kW         | 0.5..2.5               | 0.9 (if 1 kilo of salts is extracted) |
3. Results and discussions

During experimental activities we found that 0.05 kWh per equivalent gram is consumed to transfer salt ions from the desalination and concentration chambers if the process ends at 8%-level. Meanwhile, a specific ion flow rate through the cell membrane equals 4 equivalent grams per hour per m$^2$. The enough surface is then:

$$S = \frac{EVd(\varphi - 1)}{\varphi d \tau},$$

where $E$ is working absorption capacity, equivalent gram per m$^3$;
$V$ is workload volume, m$^3$;
$d$ is specific salt consumption, equivalent gram per equivalent gram;
$\varphi$ is mixing multiplicity of solution;
$\Phi$ is specific ion flow rate through the cell membrane, equivalent gram per hour per m$^2$;
$\tau$ is design duration of a concentration process, hour$\cdot$m$^2$.

The amount of facilities to handle a waste solution after an ion-exchange filter is then:

$$r = \frac{Sm}{nS_m},$$

where $n$ is number of cell membrane couples in one facility;
$S_m$ is working surface of one cell membrane, m$^2$;
$m$ is number of ion-exchange filters in one facility.

The reverse osmosis has evolved to reliable and established processes and displaced traditional desalination processes – multi-stage flash distillation (MSF). Different authors [9-11] provide an overview of recent process improvements in reverse osmosis. These improvements contribute to the cost effectiveness of the desalination process (table 2).

**Table 2.** Capital and operation & maintenance costs of desalination by multiple techniques worldwide.

| Cost type                        | MSF     | Electrodialysis | Reverse osmosis |
|----------------------------------|---------|-----------------|-----------------|
| Specific capital costs, $/m^3$   | 0.33..0.58 | 0.13..0.20      | 0.09..0.24      |
| $/m^3$ per day                   |         |                 |                 |
| O&M costs, $/m^3$ per day        | 0.77..0.79 | 0.17..0.32      | 0.24..0.33      |

Consequently, the key indicator is reduction of salts releases determine the overall economic viability of the proposed operation. This represents a savings of $650 in hourly cost for every 100 m$^3$ of treated water in the Aral Sea region on a nation-wide. Concentrating is better implemented up to salinity of 100 g/dm$^3$ due to only 0.04..0.05 kWh per equivalent gram of electricity is then consumed. Under the circumstances, specific ion flow rate through the cell membrane are within 5..10 equivalent gram per hour per m$^2$.

The results of the chemical analysis before and after treatment in the multi-stage electrodialysis module are presented in table 3.
Table 3. Test water chemical analysis results.

| Indicator | Original waste water (concentrated), mg/dm³ | Fresh water, mg/dm³ |
|-----------|---------------------------------------------|---------------------|
| Al²⁺      | 160                                         | 0.117               |
| Cl⁻       | 878                                         | 0.267               |
| SO₄²⁻     | 2040                                        | 0.189               |
| Ca²⁺      | 90                                          | 0.197               |
| pH        | 8.5–9.5                                     | 8.5–9.5             |
| TDS       | 4579                                        | 0.77                |

4. Conclusions

Presented ideas contribute to the cost effectiveness of the desalination process, and ensure a sustainable production of drinking water on long terms. Meanwhile, cost of aluminum in the cost of commodity decreases by 3-4 times, combined with consumption of electric power 1.5-2 times lower. In addition, a risk evaluation focusing on the Aral Sea region was conducted and the results showed that aluminum will build up in association with the water desalination. Pretreatment of desalination plants by pressure driven membrane processes (microfiltration, ultrafiltration and nanofiltration) also contributes to network and make-up water treatment facilities at a district heating plant [12, 13]. Compared to chemical pretreatment; new technology is applicable (1) to prevent corrosion in distillation processes, (2) fouling in a heat pump unit [14–16] and (3) further growth toxic near-bottom sediments in open water sources [17].

References

[1] Abdel-Fatah M A 2018 Nanofiltration systems and applications in wastewater treatment: Review article Ain Shams Engineering Journal 9(4) pp 3077–3092
[2] Ananieva O A, Kunitsyna T E, Shilina A S, Milinchuk V K 2012 Hydrogen Production by Chemical Decomposition of Saline Water (Poluchenie vodoroda khimicheskim razlozheniem mineralizovannoi vody) Alternative Energy and Ecology (ISJAEE) 5-6 pp 140–144
[3] Viana M M, Rangel B F, Júnior A N, Melchert M B M, Dweck J 2015 Semi-pilot scale sewage sludge pyrolysis and characterization of obtained fractions by thermal analysis Journal of Thermal Analysis and Calorimetry 123(2) pp 981–991
[4] Cao B, Zhang W, Wang Q, Huang Y, Meng C, Wang D 2016 Wastewater sludge dewaterability enhancement using hydroxyl aluminum conditioning: Role of aluminum speciation Water Research 105 pp 615–624
[5] Il’in A A, Rumyantsev R N, Veisgaim V V, Il’in A P 2016 Mechanochemical Oxidation of Aluminum for Production of Its Oxides, Hydroxides and Hydrogen Russian Journal of Physical Chemistry A 90(4) pp 764–770
[6] Razavi-Tousi, S. S., & Szpunar, J. A. (2014). Role of Ball Milling of Aluminum Powders in Promotion of Aluminum-Water Reaction to Generate Hydrogen Metallurgical and Materials Transactions E 1(3) pp 247–256
[7] Pal P, Sardar M, Pal M, Chakrabortty S, Nayak J 2019 Modelling forward osmosis-nanofiltration integrated process for treatment and recirculation of leather industry wastewater Computers & Chemical Engineering 127 pp 99–110
[8] Junussova L R 2014 Comparative Performance Analysis of Baromembranes Desalination Issues of Energy and Resource Saving 1-2 pp 254–257
[9] Echevarría C, Valderrama C, Cortina J L, Martín I, Arnaldos M, Bernat X, Castellví E 2019 Techno-economic evaluation and comparison of PAC-MBR and ozonation-UV revamping for organic micro-pollutants removal from urban reclaimed wastewater Science of The Total Environment 671 pp 288–298
[10] Kim J E, Kuntz J, Jang A, Kim I S, Choi J Y, Phuntsho S, Shon H K 2019 Techno-economic assessment of fertiliser drawn forward osmosis process for greenwall plants from urban wastewater Process Safety and Environmental Protection 127 pp 180–188
[11] Mendret J, Azais A, Favier T, Brosillon S 2019 Urban wastewater reuse using a coupling between nanofiltration and ozonation: Techno-economic assessment Chemical Engineering Research and Design 145 pp 19–28
[12] Mukhidinov D N, Junussova L R 2015 Improving the Quality of Desalinated Water with Combined Water Treatment Plant Boiler Alternative Energy and Ecology (ISJAEE) 23 167–176
[13] Chicherin S V 2018 Comparison of a district heating system operation based on actual data – Omsk city, Russia, case study International Journal of Sustainable Energy pp 1–12
[14] Chicherin S 2018 Low-temperature district heating distributed from transmission-distribution junctions to users: energy and environmental modelling Energy Procedia 147 pp 382–389
[15] Chicherin S, Volkova A, Latõšov E 2018 GIS-based optimisation for district heating network planning Energy Procedia 149 pp 635–641
[16] Junussova L R, Abildinova S K, Aliyarova M B, Chicherin S V, Junussov T J 2018 The Means to Improve Water Treatment and to Enhance Power Engineering Performance of the Water Source Heat Pump ENERGETIKA. Proceedings of CIS higher education institutions and power engineering associations 61(4) pp 372–380
[17] Siedlewicz G, Białk-Bielińska A, Borecka M, Winogradow A, Stepnowski P, Pazdro K 2018 Presence, concentrations and risk assessment of selected antibiotic residues in sediments and near-bottom waters collected from the Polish coastal zone in the southern Baltic Sea – Summary of 3 years of studies Marine Pollution Bulletin 129(2) pp 787–801