Archives of Environmental Protection
Vol. 45 no. 4 pp. 20–29

PL ISSN 2083-4772
DOI 10.24425/aep.2019.130238

Membrane processes innovation in environmental protection: Review

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Keywords: membrane techniques, microfiltration, ultrafiltration, nanofiltration, reverse osmosis.

Abstract: The partial solution for the growing contamination of the environment is the implementation of new technologies. The most of the currently operated systems for surface and groundwaters treatment as well as for wastewater treatment characterize with complex technological arrangements based on a number of unit operations. In water-wastewater management membrane processes are more often applied, especially those in which the difference of pressure at both membrane sites is used as a driving force. As an example of such application is the use of nanofiltration for groundwaters treatment at Water Treatment Plant Zawada near Dębica or the treatment of municipal landfill leachate and industrial wastewater at Eko Dolina Waste Utilization Plant in Łężyce near Gdynia (reverse osmosis unit capacity of 120 m^3/d). Municipal wastewater treatment based on membrane technologies has already been implemented at domestic wastewater treatment plant. It is especially profitable, when the load of contaminant present in a wastewater varies within a year. In the case of membrane systems use, this issue can be neglected. As an example of membrane based system may serve WWTP in Rowy n/Ustka started up in 2013 and modernized in 2017. The latest trends and developments of selected suppliers of membrane systems are also presented.

Introduction

In the 21st century fresh water may be regarded as crude oil in the 20th century, i.e. the valuable resource, which determines the development and growth of nations. Due to climate changes, population growth and inefficient water management 1) 1.1 billion of people worldwide do not have access to potable quality water and 2.5 billion of people are not equipped with sewage systems, 2) in Europe, 41 million do not have access to potable quality water and 2.5 billion of people are not equipped with sewage systems. Those are the main causes of the implementation of new membrane technologies to the production of sanitary safe potable water (Bodzek and Konieczny 2011) The partial solution for the growing contamination of the environment, i.e. air and water, is the implementation of unit operations to water and wastewater treatment systems, which enable the removal of a wide range of contaminants.

The transport of selected components through membrane is enabled by a specific driving force. Hence, in membrane separation processes this driving force can be, e.g. difference of pressure, difference of concentration or difference of electrical potential. It can be stated that in membrane techniques the transport of particles is forced by the difference of their chemical potentials at both membrane sides, while the separation is caused by difference in transport rate of particular compounds. In the most general approach, a synthetic membrane is a barrier between two gaseous or liquid solutions (mixtures), which limits the transport in such a way that substances can be exchanged between particular solutions with the rate depending on membrane or phase characteristics (Bodzek and Konieczny 2010, 2011, Konieczny et al. 2007). The development of material engineering enabled the industrial scale production of various types of membranes of various transport properties involving different driving forces.

Every treatment/separation/concentration case requires individual approach toward efficiency and economic effect. Hence, direct membrane filtration or integrated/hybrid systems, i.e. ones combined with other unit operations such as oxidation, adsorption, coagulation, etc., may be considered.

There are a number of reasons why membrane processes are proposed to treat water or wastewater or to clean air (Bodzek and Konieczny 2011):

- Worsening of quality of water resources as well as wastewater deposited to the environment,
- Increasing demand for high quality potable water related with civilization growth,
- Sharpening of regulations on potable water quality and parameters of wastewater deposited to the environment,
- Spreading and increasing contamination of the environment harmful to human bodies and life.

Membrane techniques in water treatment

The most adjusted reasons for implementation of membrane processes in industrial practice are the listed examples:

- Reverse osmosis – for water desalination/demineralization and removal of organic and inorganic micropollutants;
- Nanofiltration – for water softening and removal of organic/inorganic contaminants/micropollutants;
- Ultrafiltration and microfiltration – as a method of direct removal of suspensions, colloids and microorganisms or in integrated/combined systems for removal of inorganic and organic contaminants.

In addition to pressure-driven processes other membrane techniques are also applied. For example, forward osmosis (FO) and pervaporation (PV) are recently proposed for desalination and removal of some micropollutants and electrodialysis (ED) and liquid membranes for inorganic compound removal.

Water desalination and demineralization

Distillation methods are conventional and quite commonly used techniques for water desalination, among which one may distinguish the most commonly used are:

- Multistage flash distillation (MSF);
- Multiple effect distillation (MED);
- Among others: vapor compression distillation (VC).

Among membrane methods one may find reverse osmosis (RO) and electrodialysis (ED). Considering the share of particular processes in global desalination practice, membrane processes are the most commonly used, as it is shown in Figure 1 (Kasaeian et al. 2019).

Moreover, operational costs of particular desalination/demineralization methods are different. Distillation methods characterize with high energy consumption, regardless of salt concentration in water.

The following rules are usually applied to water desalination/demineralization systems design (Bodzek and Konieczny 2005, Helal 2009, Magdziorz and Seweryński 2004):

1. combine reverse osmosis with thermal methods for lowering the cost,
2. introduction of to water desalination/demineralization,
3. reverse osmosis with ion exchange (electrodeionization).

The combination of reverse osmosis with thermal methods is advantageous as the processes share particular technological elements, e.g. feed water source and its preliminary and final treatment stages, mixing of permeate with distillate, concentrates utilization, etc., what results in:

- Energy consumption and costs decrease by 15%,
- One stage reverse osmosis operation as worse quality permeate may be mixed with distillate.

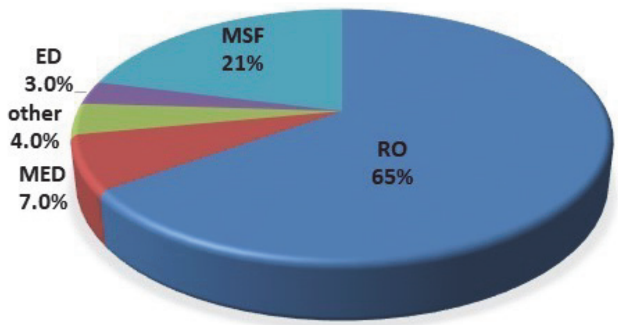

Fig. 1. Percentage share of individual methods applied in water desalination (Kasaeian et al. 2019)

Additional benefits of combined systems are the effective use of power and desalinated water. The water can be stored, whereas the waste heat (low pressure water vapor) from MSF and/or power plant can be utilized in RO. The combination of RO and thermal method in RO-thermal method-NaCl crystallization arrangement is applied for concentration of RO retentate by means of thermal method accompanied by water recovery and selective NaCl crystallization. Such arrangement can be used to treat highly saline inland water as the main purpose is to eliminate salts from water, preferably in the form of trade products. The example of such system is the plant for mine water desalination started up in Dębieńsko in 1995. It is based on a combined system, which comprises of (Bodzek and Konieczny 2010, Helal 2009, Konieczny et al. 2007, Magdziorz and Seweryński 2004) reverse osmosis, thermal concentration and NaCl crystallization.

The use of nanofiltration in water desalination as a stage preceding RO allows to prevent the risk of calcium sulphate crystallization and enables to obtain high concentration of salt in retentate (up to 150 g/L). In the case of direct RO, the process can be only carried out until the concentration of salts in retentate reaches 70 g/L. Combined processes with NF for improving efficiency and capacity are the following:

- NF – RO
- NF – MSF
- NF – RO – MSF

The advantages of such systems:

– permeate and distillate recovery rate increase up to 70 or 80%, respectively,
– no need for additional chemicals use (e.g. antiscaling agents),

Additionally, one may consider the use of RO and MSF as separate processes, whereas water produced by these systems can be collected in one tank as well as concentrates.

An exemplary arrangement of a hybrid system with NF and RO as well as with MSF is shown in Figure 2 (Helal 2009).

For deep water demineralization (steam boilers) hybrid systems like reverse osmosis-ion exchange/electrodeionization are usually used, what is shown in Figure 3 (Bodzek and Konieczny 2005).

Such the solution is adjusted by a number of factors, including:

- individual selection of preliminary feed water treatment before RO (usually coagulation-flocculation-sedimentation), which depends on raw water type,
- 99.5% removal of total dissolved substances by RO, which is crucial for proceeding processes (IE, EDI) efficiency,
- effective performance in the case of raw water of salinity >350–450 mg NaCl/L,
- ecological aspects (energy consumption, side stream amount and utilization).

Another example of water desalination/demineralization plant is the installation operated in the Kozienice Power Plant. The installation comprises of RO system and ion exchange. The produced water is used to feed steam boilers (Energotechnika 2011).The treatment process comprises of several stages, and water parameters are collected in Table 1.

I[st] stage, preliminary treatment: filtration at slit filter (1000 mm) – NaOCl disinfection – coagulation (PIX111) – enhanced sedimentation;

II[nd] stage, three step filtration: sand-anthracite filters – carbon filters – candle filter;

III[rd] stage, preliminary desalination at five RO modules (BW30LE440 – capacity: 50–60 m^3/h);

IV[th] stage, final demineralization: cationite – anionite – bifunctional ionite;

Process costs estimate has to include:

- Desalination technology type, raw water quality, capacity and localization of a plant,
- Manpower competences and energy costs.

Operational costs of desalination of water of salinity up to 4g/L in 1980s were equal to ca. 0.5 USD/m^3, while now they are 0.2–0.35 USD/m^3. For seawater (salinity 35–42 g/dm^3) it was above 1 USD/m^3 in the 1980s and 1990s, and now it is 0.5–0.8 USD/m^3 (Bodzek and Konieczny 2011).

Water softening-nanofiltration (NF)

Due to standards, potable water should characterize with hardness of 60–500 mg $CaCO_3$/L. the standard for magnesium is 30 mg/L. The excess of hardness in water is harmful for human health. Nanofiltration membranes characterize mainly with:

- separation of bivalent ions from monovalent ones,
- retention of organic compounds of M>300–500 Da.

The results of water softening indicate a possibility of recovery of soft or slightly hard water (total hardness <200 mg $CaCO_3$/L) from hard and very hard water (total hardness >300 mg $CaCO_3$/L). It has been confirmed by the research carried out at Silesian University of Technology with use of NF membrane by Osmonics (Bodzek and Konieczny 2011).

Nanofiltration seems to be a suitable and economically adjusted process for simultaneous removal of hardness and natural organic matter (NOM), what is shown by the results presented in Table 2 obtained during research carried out in 2002 using NF200B membrane by Filmtec/DOW (Van der Bruggen and Vandecasteele 2002).

The practical use of nanofiltration treatment with use of nanofiltration membrane dedicated mainly to removal of hardness (500 mg $CaCO_3$/L) is carried out at Water Treatment

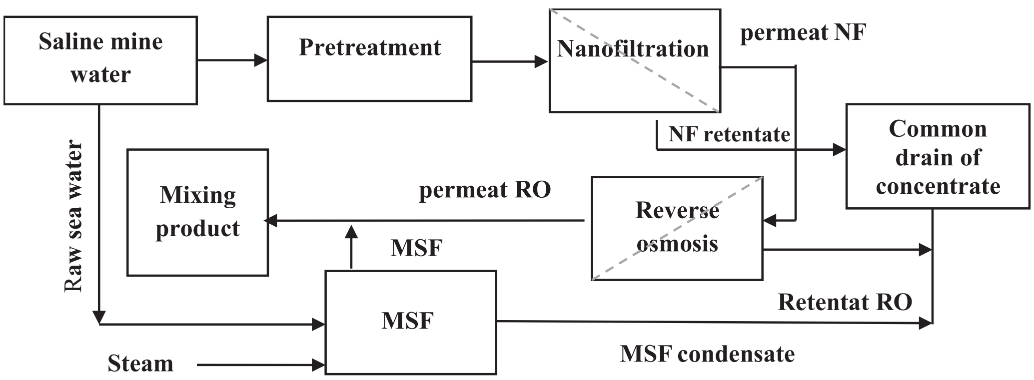

Fig. 2. Hybrid NF/RO/MSF system for water desalination (Helal 2009)

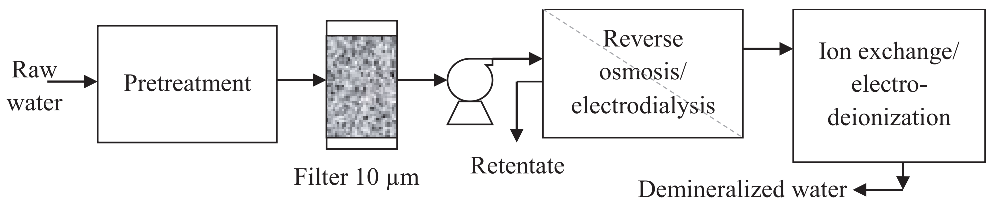

Fig. 3. The scheme of a typical installation of water demineralization with the use of reverse osmosis (Bodzek and Konieczny 2005)

Table 1. The efficiency of water treatment in the Kozienice power plant (Energotechnika 2011)

Treatment stage	Parameter	Permissible level	Obtained level
Sedimentation tank	Total suspended solids, mg/l	5	<2
Sand-anthracite filter	Total suspended solids, mg/l	0.5	NTU<1.5
Precoat filters	TOC, mg/l SDI	<3 3	<2 <3
RO modules	SiO_2, ppb Salinity, µS/cm	800 50	<50 <30
Desorbers	CO_2, ppm	10	<2
Bifunctional ionites	SiO_2, ppb Salinity, µS/cm	20 0.1	<10 <0.1

Plant Zawada near Dębica. The photograph of the system is shown in Figure 4 (ABT 2013).

The below scheme presents the groundwater treatment at WTP Zawada n/Dębica:

Groundwater → Removal of Fe and Mn → Carbon filter → Nanofiltration → Final treatment → Potable water

Parameters of the device:
– Capacity of permeate (product) – 50 m^3/h at temp. 15°C,
– Capacity of retentate (waste) – 12.5 m^3/h at recovery rate 80%,
– Operational pressure 0.8–1.2 MPa,
– Nanofiltration membranes Desal 8×40" HL8040F400.

The installation also contains chemical washing and disinfection systems for membranes maintenance.

Ultrafiltration (UF) and microfiltration (MF)

In 2000, more than 2 M m^3/d of potable water was produced with use of low pressure driven membrane methods, i.e. microfiltration and ultrafiltration, and currently this amount is much higher. The use of UF/MF as a single stage or a combined system for water treatment to potable or industrial purposes is continuously developed and improved. The importance of using membranes in water and wastewater treatment can be illustrated by comparing the world's sales in different fields of technology. For example, the sales of membranes and membrane modules according to McIlvaine Company report: "RO/UF/MF World Markets" in 2006 was over 7.6 billion, while in 2010 this value increased to $10 billion, with 50% of this amount connected with Water and wastewater technology.

Pore size of MF and UF membrane is often too large for direct, effective retention of dissolved or even colloidal compounds present in water. Hence, integrated systems combining UF/MF with other unit operations listed below are usually used:

(A) coagulation/precipitation,
(B) adsorption,
(C) polymer complexation,
(D) bonding with surfactants.

The example of such a system is the combination of coagulation/precipitation-MF, which is especially useful for

Table 2. Parameters of water before and after nanofiltration (Van der Bruggen and Vandecasteele 2002)

Load indicator	Initial concentration	Removal rate R, %
DOC, mg/l	20.4	98.2
UVA 254nm, 1/m	46.0	98
Vis 436nm, 1/m	1.6	98
AOX formation potential	582	96.7
THM formation potential	506	95.3
Specific conductivity, mS/cm	2230	73.3
Ca^{2+}, mg/l	329.6	77.5
Mg^{2+}, mg/l	55.3	90.3

Fig. 4. The photograph of installation for water treatment operated at WTP Zawada n/Dębica (ABT 2013)

the removal of fluorine and heavy metals (As, Sb, Hg, etc.) from aquatic environment. The operation of the system may be separated into two stages:

- I[st] stage, co-precipitation of aluminum and fluorine: Al^{3+}+(3-x)OH- +xF- → $Al(OH)_3^-$xFx↓ and precipitation of metals hydroxides – $Me(OH)_2$;
- II[nd] stage, micro- or ultrafiltration;

The application of the combined system of adsorption – MF is based on the use of ion exchange resin of low grain size, e.g. MIEX of granulation 150 µm (F, NO^{3-}, As(V), Cr(VI)) or Dowex and Amberlite of granulation 20 µm (especially useful for boron (B) adsorption). The activated carbon may also be used for heavy metals adsorption. The stages of the process are adsorption – MF/UF – regeneration of resin/activated carbon (Mamo et al. 2018).

Another possibility is the combined system mentioned in (C), in which UF/MF process in enhanced with polymers (PEUF). The process is based on binding of metal ions and anions with polymers soluble in water to form complex compounds of molecular weight higher than UF/MF membrane pore size. Complexing polymers or polyelectrolytes may be applied. The scheme of the process of ions removal based on four stages is shown in Figure 5 (Korus 2012).

The enhancement of UF/MF with surfactants (MEUF) mentioned in (D) may also be applied in order to assure the efficient removal of contaminants like: NO^{3-}, ClO^{4-}, Cr(III), As, metals. In such hybrid system, water containing one of the mentioned ions is mixed with a solution of a surfactant of concentration above the critical micelle concentration (CMC) and the binding of ions in micelles occurs. The diameter of micelles is usually higher than the diameter of UF/MF membrane pore size, hence the separated ion remains with a micelle at a retentate site (sieving mechanism) (Korus 2012). The efficient removal of ionic water contaminants depends on type and concentration of polymer/surfactant, UF/MF membrane type, contaminant concentration, pH and ionic strength and process operational parameters.

The excess of suspended solids present in water may efficiently be decreased to permissible standard level (i.e. 1 NTU) by means of NF/UF. Additionally, microorganisms, bacteria and colloidal contaminants are also removed (Bodzek et al. 2019, Bodzek and Konieczny 2018, Chen and Chen 2016). The example of such application is modernization of WTP in Sucha Beskidzka where bacteriological contaminated feed water, was intaken from the Stryszawka river. PALL Aria AP6 membranes arranged in modular system are used at the plant. The filtrate recovery rate reaches 99% depending on feed water parameter. The capacity of the system equals 130 m^3/h, i.e. 1,135,68 m^3/year (PALL Corporation 2006, Szczęch 2006). The scheme of another membrane based installation of capacity 470 m^3/h operated at WTP Jarosław (PALL Corporation 2009).

The scheme of modernized system for potable water production in Sucha Beskidzka is shown in Figure 6 (Szczęch 2006).

Similar solutions have also been implemented at WTP Jarosław of capacity 470 m^3/h and WTP Biała Dolina of capacity 6.5 m^3/h (Bodzek and Konieczny 2005, Konieczny and Bodzek 2014a, b, c, PALL Corporation 2009).

Bacteria and viruses may periodically appear in surface water, and in practice they may not be completely eliminated by UF membranes, due to:

- biological recontamination of water at permeate site,
- imperfection of membranes and membrane modules,
- penetration of membrane pores by microorganisms of cells much larger than membrane pore size due to deformation pressure accompanied by cellular fluid evolution and maintenance of cell membrane tonus (Fig. 7) (Sosnowski et al. 2004).

The applied membrane systems produce potable water of quality corresponding to the requirements established in The Regulation of the Minister of Health from 7[th] of December 2017 (Dz. U. 2017) on quality of potable water dedicated to human consumption. The Regulation defines physico-chemical, microbiological and organoleptic standards, which should be completed by water treated for potable purposes.

Examples of different types of module and membranes are presented in Figure 8.

The World's largest membrane producers and suppliers are: Dow Chemicals Filmtec U.S.A, Toray Japan, Hydronautics U.S.A , Koch U.S.A. Lenntech Dania, Desal U.S.A., Pall U.S.A., Ceramic, Ge Power&Water (ZeeWeed), Intermasz – ami, Silhorko-Eurowater A/S Denmark, Hydronautic, Pci Membranes ltd. (Ang et al. 2015, Konieczny and Bodzek 2014a, b, c, PALL Corporation 2009).

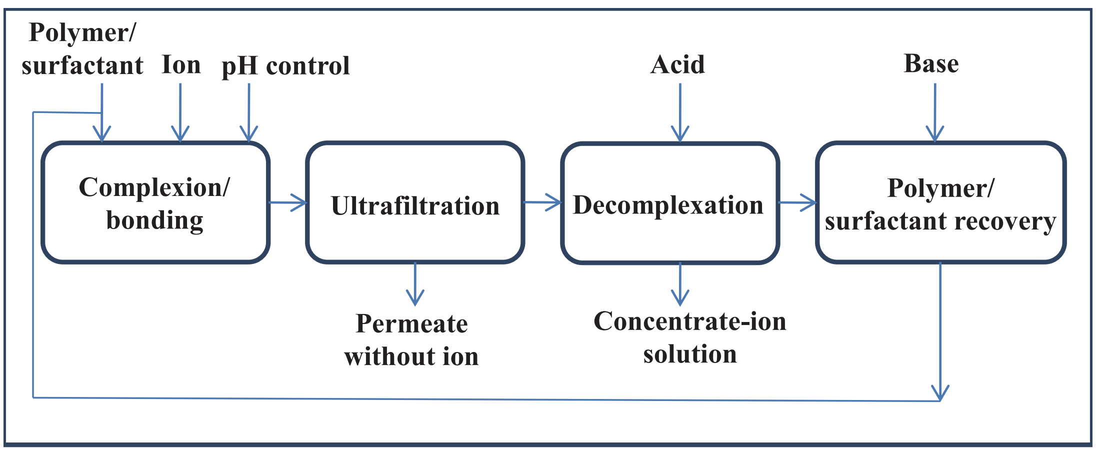

Fig. 5. The scheme of the combined process: UF membrane/complexation (Korus 2012)

Municipal wastewater treatment

Nowadays scientific and industrial activities in the field on wastewater treatment are focused on the development of so called "green technologies", i.e. environmental friendly systems. The special attention is given to solutions which allow for minimization of natural materials and enable a recovery of valuable components and feedstock. Such an approach requires use of a range of separation processes, among which membrane processes are more and more often applied.

Membranes in municipal wastewater treatment

Municipal wastewater treatment based on membrane technologies has already been implemented at domestic wastewater treatment plant (Mamo et al. 2018). It is especially profitable, when the load of contaminant present in a wastewater varies within a year. In the case of membrane systems use, this issue can be neglected. The example of membrane based system may be WWTP in Rowy n/Ustka started up in 2013 and modernized in 2017. The installation operated in this resort, where significant wastewater loads are observed in summer, is

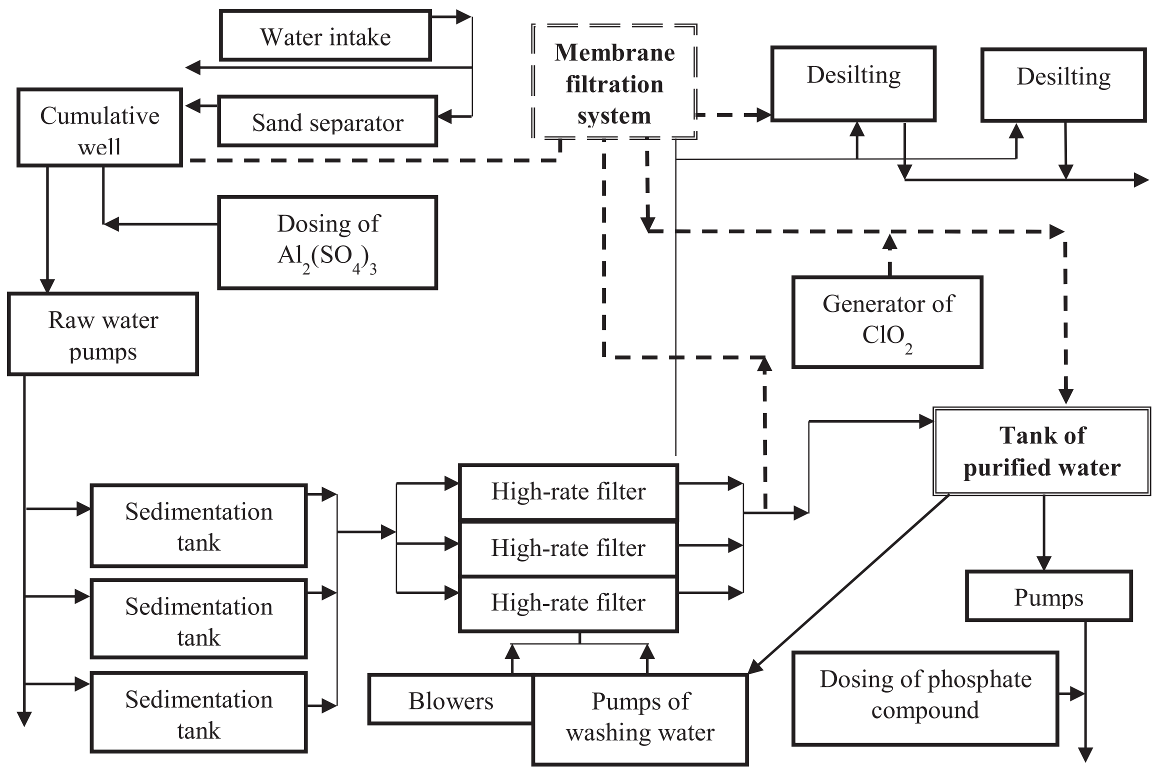

Fig. 6. The scheme of the system of potable water production Sucha Beskidzka (Szczęch 2006)

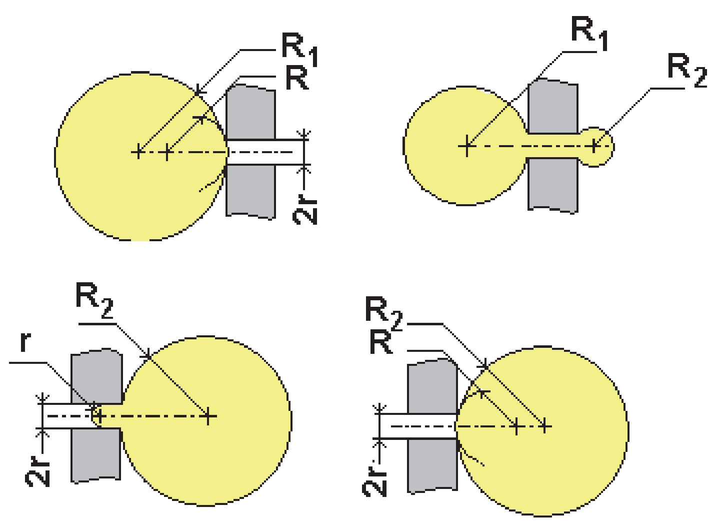

Fig. 7. The phenomenon of deformation of microorganisms and penetration of the membrane pores (Sosnowski et al. 2004) (r – cylindrical straight pore radius in membrane (10–100 nm), R – circular radius of the micro-organism (3–150·10³ nm))

Fig. 8. Examples of different types of module and membranes

shown (Piaskowski and Nowacki 2017). The regular number of citizens equal 7,500, while in summer season (June–September) it increases six fold.

Another example of application of RO is sewage treatment plant is EC Jaworzno Power Plant. The installation with capacity of 2×60 m^3/h comprised of double pass RO, membrane degassing, UV 185 nm and polishing with EDI was operated at the plant. After 12 weeks of operation, TOC was less than 0.001 mg/L, and sodium and silica below 0.002 mg/L (Eurowater 2017).

Municipal landfill leachate treatment

Leachate (according to definition given in EU Directive from 26th of April 1999) is every liquid which drains through deposited wastes and outflows remains at a landfill site. Municipal landfill leachate characterizes with a high contaminants load and instable composition, which depend on type of deposited wastes, landfill size, age and localization, isolation type, fall water separation method, climate, fall water pH and season. In general, leachate reveals high salinity, organic contamination indicators: BOD_5 and COD, high concentration of ammonium and organic nitrogen, high alkalinity and total hardness as well as significant heavy metals content. Systems operated with use of membrane methods, including two stage reverse osmosis and hybrid arrangements: biological treatment – (ultrafiltration) – reverse osmosis or nanofiltration, are proposed to treat leachate. RO retentate should be utilized by evaporation and drying and next deposited as a hazardous waste.

In 2009, Ortocal company designed and constructed a modernized installation to municipal landfill leachate treatment by means of reverse osmosis of capacity 120 m^3/d in Waste Utilization Plant Eko Dolina in Łężyce. 12 membrane modules of total membrane area equal to 307 m^2 were installed. Nowadays, it is the largest leachate treatment site based on reverse osmosis operated in Poland.

Leachate treatment systems are operated at maximum pressure of 6 MPa and involve use of ST modules by ROCHEM. As in the case of leachate treatment both, influent flow rate and contaminants load are unstable, the operational parameters of the installation are adjusted to the current influent parameters. In Figure 9 the scheme of the installation for leachate treatment by Ortocal is shown (P.H.U. Ortocal 2010). The installation contains two stage reverse osmosis to direct leachate treatment, whereas the obtained permeate is additionally treated in separate RO modules. The company implements new investments in WUP in Siedliska n/Ełk, in MWUP in Stary Las n/Starogard Gdański.

The parameters of the treated leachate are shown in Table 3 (P.H.U. Ortocal 2010). One has to note that the obtained parameters are better than the established ones.

Modernization of industrial leachates and wastewaters pretreatment plant in EKO Dolina was finished on 29th of March 2017 (P.H.U. Ortocal 2010).

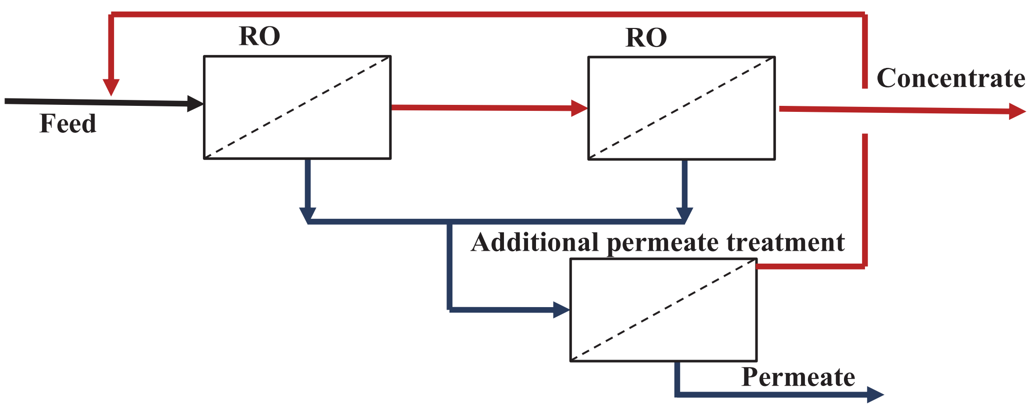

Fig. 9. The scheme of the leachate treatment installation by Ortocal (P.H.U. Ortocal 2010)

Table 3. The results of the leachate treatment in WUP Eko Dolina in Łężyce (P.H.U. Ortocal 2010)

Parameter	Unit	Raw leachate	Permeate	
			Established value	Obtained value
pH	–	7.8	6–8.5	6
Specific conductivity	μS/cm	24,700	400	217
BOD_5	mg O_2/l	182	30	7.0
COD	mg O_2/l	3,490	40	14.3
Chlorides	mg Cl/l	3,481	100	40.0
Ammonium nitrogen	mg NH_4/l	2,230	20	22.2
Total nitrogen	mg N/l	2,420	30	22.2
Phosphates	mg PO_4/l	54.0	20	<0.15
Total phosphorus	mg P/l	18.0	10	<0.05
Sulphates	mg SO_4/l	1,310	50	1.64

Summary

The currently observed changes in water and wastewater treatment may be regarded as future tendencies in these technological fields. The implementation of membrane processes to treatment of water for potable and industrial purposes is one of the most important trends. The efficiency of membrane processes allows to assume that they will either supplement or substitute currently used processes. The main limitation of common membrane separation implementation is the economy. Pressure driven membrane processes may be applied to ground and surface water treatment and, additionally, they enable the management of hard to treat fall water, recirculation of wastewater, closing of water loops and utilization of mine waters. Membrane processes should be used as independent treatment systems or as a significant element of conventional ones, as e.g. at WTPs in Sucha Beskidzka and Jarosław. Membrane processes can be also used as water polishing systems for individual households due to the **increasing** retention time of water in pipelines. The discussed examples of already operated systems confirmed these approaches.

The improvements in technology and designing of reverse osmosis system as well as the development of alternative energy sources have caused desalination/demineralization by means of RO become ecologically friendly method for drinking/deionized water production in many regions of the world, especially in ones of limited water resources.

In the 1980s nanofiltration as a method for water softening, in regard to simultaneous removal of water hardness and organic micropollutants, gained special interest.

The use of microfiltration and ultrafiltration in the removal of inorganic and organic micropollutants is possible with their arrangement as an integrated system with: (1) coagulation or adsorption, (2) polymer complexation, (3) binding with surfactants.

The production of sanitary safe water of stable and high quality by means of membrane separation is a good alternative for conventional disinfection techniques, as NF, UF and MF membranes are efficient barrier for pathogenic protozoa cysts, bacteria and partially viruses. It allows for the decrease of chlorine doses used in final disinfection. Moreover, membrane techniques are used in many industrial branches. They are successfully applied in food industry (juice, dairy products), in medicine (kidneys dialysis, ultra-pure water for medical purposes) as well as in metal, machinery, energy industries and many others.

Membrane technology is a strategic sector in which the EU is well positioned in terms of scientific and technical (S&T) excellence, albeit still under-represented in manufacturing presence. Innovation derived from research can provide a springboard for future growth in market share. Europe has a solid reputation in water sciences and technologies. In the domain of water treatment membranes, its strengths lie mainly in the competitiveness of its engineering industry, especially with regard to system integration for desalination and wastewater treatment. In particular, the EU benefits from a network of small and medium-sized enterprises (SMEs) that are active in this field and are often well connected to experienced academic centres, which together form a wide and world-class research community. Building on this S&T base is crucial, not only to meet Europe's own water needs, but also – in line with the Europe 2020 strategy – to contribute to the overall greening of the European economy, and to boost the share of manufacturing industry in a global market worth over EUR 300 billion (European Commission).

References

ABT (2013). Branded materials office projects, (http://www.abt.pl/ (5.06.2019)). (in Polish)

Ang, W.L., Mohammad, A.W., Hilal, N. & Leo, C.P. (2015). A review on the applicability of integrated/hybrid membrane processes in water treatment and desalination plants, *Desalination*, 363, pp. 2–18, DOI: 10.1016/j.desal.2014.03.008.

Bodzek, M. & Konieczny, K. (2018). Membranes in organic micropollutants removal, *Current Organic Chemistry*, 22, pp. 1070–1102, DOI: 10.2174/1385272822666180419160920.

Bodzek, M. & Konieczny, K. (2011). *Removal of inorganic pollutants from water environment by means of membrane methods*, Seidel--Przywecki, Warszawa 2011. (in Polish)

Bodzek, M. & Konieczny, K. (2010). The application of membrane techniques in drinking water treatment, I – Removal of inorganic pollutions, *Technologia Wody*, 1, pp. 9–21. (in Polish)

Bodzek, M. & Konieczny, K. (2005). *The application of membrane processes in water treatment*, Oficyna Wydawnicza Projprzem--Eko, Bydgoszcz 2005. (in Polish)

Bodzek, M., Konieczny, K. & Rajca, M. (2019). Membranes in water and wastewater disinfection – review, *Archives of Environmental Protection*, 45, pp. 3–18, DOI: 10.24425/aep.2019.126419.

Chen, D. & Chen, Q. (2016). Virus retentive filtration in biopharmaceutical manufacturing, *PDA Letters*, pp. 20–22, DOI: 10.1016/j.memsci.2017.03.043.

Dz. U. 2017, poz. 2294. Regulation of the Minister of Health of 7 December 2017 on the quality of water intended for human consumption. (in Polish)

Energotechnika, Branded Materials, Knurów 2011. (in Polish)

European Commission, EUR 24552 – Membrane technologies for water applications highlights from a selection of European Research Projects, Luxembourg: Publications Office of the European Union, ISBN 978-92-79-17087-4, DOI: 10.2777/25163.

Eurowater (2017). Energy efficient water treatment E07A-42A-UK1, (www.eurowater.com (5.06.2019)).

Helal, A.M. (2009). Hybridization – a new trend in desalination, *Desalination and Water Treatment*, 3, pp. 120–135, DOI: 10.5004/dwt.2009.263.

Kasaeian, A., Rajaee, F. & Yan, W.-M. (2019). Osmotic desalination by solar energy: A critical review, *Renewable Energy*, 134, pp. 1473–1490, DOI: 10.1016/j.renene.2018.09.038.

Konieczny, K. & Bodzek, M. (2014a). Practical application of membrane techniques to pressure in the economy water and wastewater, *Rynek Instalacyjny*, 3, 4, pp. 73–77, 91–93. (in Polish)

Konieczny, K. & Bodzek, M. (2014b). Pressurized membrane techniques in the economy water and wastewater, *Rynek Instalacyjny*, 1–2, pp. 80–85. (in Polish)

Konieczny, K. & Bodzek, M. (2014c). Pressurized membrane technique in industrial wastewater and leachate from municipal dumps, *Rynek Instalacyjny*, 6, pp. 76–77. (in Polish)

Konieczny, K., Sąkol, D., Bodzek, M., Korycki, M. & Rajca, M. (2007). Comparison of the effectiveness of selected coagulants to remove organic substances in the process of coagulation of hybrid/micro filtration, *Instal*, 4, pp. 53–66. (in Polish)

Korus, I. (2012). *The use of ultrafiltration assisted polymers for the separation of heavy metal ions*, Wydawnictwo Politechniki Śląskiej, Gliwice 2012. (in Polish)

Mamo, J., García-Galán, M.J., Stefani, M., Rodríguez-Mozaz, S., Barceló, D., Monclús, H., Rodriguez-Roda, I. & Comas, J. (2018). Fate of pharmaceuticals and their transformation products in integrated membrane systems for wastewater reclamation, *Chemical Engineering Journal*, 331, pp. 450–461, DOI: 10.1016/j.cej.2017.08.050.

Magdziorz, A. & Seweryński, J. (2004). *Concentration of mineralized water by membrane processes with simultaneous crystallization of sulphate salts*, Monografie Komitetu Inżynierii Środowiska PAN, 22, pp. 83–104. (in Polish)

PALL Corporation (2009). Water Treatment System PALL Aria AP-6 "Jarosław". (in Polish)

PALL Corporation (2006). Water Treatment System PALL Aria AP-6 project version 01, "Sucha Beskidzka", pp. 1–18. (in Polish)

P.H.U. Ortocal (2010), (www.ortocal.pl (1.03.2017)). (in Polish)

Piaskowski, K. & Nowacki, M. (2017). Selected aspects of the operation of membrane bioreactor MBR, *Technologia Wody*, 4, pp. 38–45. (in Polish)

Sosnowski, T., Suchecka, T. & Piątkiewicz, W. (2004). *Penetration of the cell through the microfiltration membrane*, Monografie Komitetu Inżynierii Środowiska PAN, 22, pp. 359–367. (in Polish)

Szczęch, K. (2006). Modernization of SUW Sucha Beskidzka – layout membrane filters, *Ochrona Środowiska BMP*, 4, pp. 24–28. (in Polish)

Van der Bruggen, B. & Vandecasteele, C. (2002). Distillation vs. membrane filtration: Overview of process evolutions in seawater desalination, *Desalination*, 143, pp. 207–218, DOI: 10.1016/S0011-9164(02)00259-X.

Innowacyjne procesy membranowe w ochronie środowiska: Przegląd

Streszczenie: Częściowym rozwiązaniem wzrastającego zanieczyszczenia środowiska wodnego jest wdrażanie nowych technologii. Większość współczesnych dużych systemów uzdatniania wód powierzchniowych i podziemnych oraz oczyszczania ścieków charakteryzuje się bardzo złożonymi układami technologicznymi zakładającymi sekwencję wielu procesów. W gospodarce wodno-ściekowej w coraz to większym zakresie wykorzystywane są procesy membranowe, przede wszystkim te, których siłą napędową jest różnica ciśnień po obu stronach membrany. Przykładem jest między innymi zastosowanie nanofiltracji do uzdatniania wód głębinowych w SUW Zawada k. Dębicy oraz oczyszczanie odcieków z wysypisk odpadów stałych i ścieków przemysłowych technologią membranową w zakładzie Unieszkodliwiania Odpadów Eko Dolina w Łężycach k/Gdyni (wydajność RO 120 m^3/dobę). Oczyszczanie ścieków komunalnych w oparciu o technologie membranowe zostało już wdrożone w krajowych oczyszczalniach ścieków. Jest to szczególnie opłacalne, gdy ładunek zanieczyszczeń obecnych w ściekach waha się w ciągu roku. W przypadku zastosowania systemów membranowych, problem ten można pominąć. Przykładem wdrożenia systemu membranowego może być WWTP w Rowach k/Ustki, którą zbudowano w 2013 r. i zmodernizowano w 2017 r. Ponadto przedstawiono najnowsze rozwiązania oraz trendy rozwoju w niektórych firmach realizujących technologie membranowe u klientów.