Membrane technology – past, present and future within the water industry

T. Peters*

The pressure driven membrane processes microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO) have become definitively important instruments in water management and environmental engineering. Their performance has been comprehensively verified from a technical and economical, as well as an ecological, point of view. These processes can be considered nowadays to be well-proven and very successful tools of chemical engineering, allowing for example to overcome water scarcity and to prevent water pollution, or to enable recovery and reprocessing of valuable substances. In combination with other processes the remaining water quantity can be significantly reduced by multiplied usage of the water, thus saving costs, but also facilitating the realization of environmental sustainable zero liquid discharge (ZLD) procedures.

This development is partially based on results obtained during the operation of RO systems that were designed in the early days of the technology for the desalination of seawater (trendsetting patent 1964). Details addressing these membrane processes, example for their area of application in the past, present and expected developments, are considered for the discussion of decision supporting criteria for the selection of these technologies.

1. Introduction

Membrane technology for the treatment of water and wastewater shows impressively how innovative, future-oriented and economically meaningful environmental protection technology can be. In the past 100 years of modern water and wastewater treatment for households and enterprises, no other new technology has been introduced that offers so many positive effects like membrane technology /1/.

Numerous different problems in water treatment can be solved, simultaneously resulting in significant better cleaning of wastewater. Due to the wide range of available membranes and modules, including open channel systems for niche applications /2/, technically suitable systems for nearly every type of problem in water treatment can be found. Membrane technology also allows for internal recovery and reprocessing of solid and dissolved substances, thus creating added value.

On one side the increasing world population, the rising living standard and the expanding industrialization are the main causes of the ever increasing demand for potable water and for water of high quality for industrial applications. The areas affected are not only arid regions of the world with their chronic water deficiency, but also at an increasing rate the urban agglomerations and industrial centres in which the capacity limits of natural supplies have almost been reached /3/.

On the other side, the phrase „WATER IS LIFE“ is generally used nowadays to very clearly express the problems of a lack of potable water. However, the statement should be rephrased to „NO LIFE WITHOUT CLEAN WATER IN SUFFICIENT AMOUNT“, as this helps to remind mankind that nearly every type of contamination can at least be a source for water pollution, and thus a danger for the basis of life. At the same time is clarified that water produced artificially has to meet well defined quality standards /4/, which is possible using membrane technology.

2. Advanced Water Management Strategies

In many regions it is not possible anymore to satisfy the growing water demand by conventional methods of water procurement and processing. Therefore, an increased utilisation of advanced separation techniques like membrane technology is called for, based on three main strategies /5/.

2.1 PRODUCTION: production of potable water from saline and polluted waters in order to increase the amount of good quality water available in addition to the natural water resources. Example are:
- Desalination of sea water or brackish water (RO)
- Separation of sulphate from drinking water (NF)
- Improved purification of river water (UF)
- Disinfection of surface water (UF)

2.2 REUSE: improved purification of slightly polluted wastewater in order to increase the exploitation potential, respectively to reduce the consumption of potable water by recycling or reuse of the purified water. Examples are purification of:
- Pre-treated industrial wastewater for recycling in a semi-closed loop (low pressure RO)
- Filter backwash water in swimming pools for use as bathing water (low pressure RO)
- Filter backwash water in water works to increase the production of potable water (UF)
- Effluent of sewage treatment plants and use for irrigation purposes (UF)
- Gray water on ships and use as technical water (UF)
- Gray water at hotels and use for toilet flushing and irrigation (UF)

2.3 PROTECTION: the prevention of further contamination of the water resources by improved purification of waste water and contaminated water. Example are purification of:
- Landfill leachate (RO)
- Effluent from sewage treatment plants to reduce contamination in the receiving river (UF)
- Black water on ships or at hotels to protect the environment (membrane bioreactor (MBR) based on UF)

The growing concern in recent years around the world regarding environmental pollution, more stringent legal requirements regarding the quality of drinking water or bathing water and the anticipation of tightened global waste discharge regulations have been further driving forces for the increasing acceptance and wider use of these technologies /6, 7/.

* Dr.-Ing. Thomas Peters
Consulting for Membrane Technology and
Environmental Engineering
Broschur: 91.41462 Neuss, Germany, dr.peters@consulting@t-online.de
Similar to the development of RO technology as a classical application for the desalination of seawater to produce potable water, the membrane processes MF, UF and NF become important instruments in water management and environmental engineering. The kind of process to be installed as a main step or in combination with other technologies for a specific application depends on the type of contaminants to be separated from the water to be treated and the quality requirements imposed for the produced water.

3. Membrane processes

Even if membrane processes seem to be, or are, well known, and have been described in countless articles and descriptions, some technological details and nomenclature differ in publications. Therefore, some definitions and technical details that are usually used among experts are described here, together with some considerations resulting from long term experience in the field.

The membrane processes considered are pressure driven separation processes, where the driving force is a pressure difference across the membrane. With the membrane the water to be treated is separated into a stream of filtrate (the usual denomination for the product water at MF and UF) or permeate (the usual denomination for the product at NF and RO), respectively, and a remaining quantity of retentate, also denominated as concentrate (Figure 1). In the retentate the contaminants or dissolved and undissolved components respectively contained in the feed water, which have been rejected by the membrane, are accumulated.

Usually these processes are operated in the so-called crossflow mode that allows control of the formation of deposits or layers on the membrane surface, and a reduction in scaling, fouling and biofouling in a certain range. Thereby the negative effects of the inevitable biofouling in long term operation can be influenced positively using innovative cleaning procedures, e.g. air bubbles. Such air bubble enhanced membrane cleaning has already been investigated ~30 year ago in context of an RO based technique for the reduction of nitrate in drinking water using a process that nowadays is addressed as ZLD. For UF applications it was introduced years later as “Air-Pulsing”.

In crossflow mode the liquid to be treated is pumped over the membrane(s) and split into the two streams mentioned above; the operating pressure provided by the pump and achieved by adapting the cross-section of the pressure control valve to the necessary level. For operation in deadend mode (possible only for MF and UF) this pressure valve is completely closed at well specified intervals. However, in all cases, flushing, rinsing, backwash, chemical enhanced backwash and/or cleaning activities need to be adequately selected and optimised during long term operation. Thereby it should be recalled, that the most important feature for the successful operation of membrane systems is the possibility to realise a highly efficient periodic cleaning of the membranes.

The membranes used in these processes can be considered as well defined barriers. This allows for a continuous and reproducible control with robust measuring instruments. At the same time the barrier function of the membranes guarantees that a high quality of filtrate or permeate is always achieved, which is nearly independent from concentration changes of contaminants in the feed.
Plants equipped with membranes show a high operating stability, as the process is switch operated. Also start-up and shutdown need no special attention and are realized in few minutes. The modular design of the systems is the basis for high flexibility against changes of the volume of water to be treated and for a small foot-print for the plant itself. These features result from the properties of the membranes and from their combination with an appropriate module configuration and plant design, that have to be strictly adapted to the needs of each specific application /5/. The basis for selection are the capabilities of the processes.

3.1 Microfiltration (MF): the filtration process with the least restrictive membrane type. Its applications include bacteria and pigment removal and removal of other particulates with particle sizes in the submicron range. Porous membranes are used with pore sizes in the range of about 0.1 to 1.0 μm (1 mm = 1000 μm); the most common for commercial membranes is an average pore size of 0.2 μm. Transmembrane pressure are from 10 to 500 kPa (0.1 to 5 bar), usually around 100 kPa. In special applications like an MBR, a vacuum in the range of, for example, 0.1 bar is applied.

3.2 Ultrafiltration (UF): these membranes can remove bacteria and viruses and can separate macromolecules like proteins, as well as colloidal silica and pyrogens. The typical molecular weight cut-off ranges from 5,000 to 200,000 g/mol. Usual pore size is in the range of 0.05 to 0.02 μm. Transmembrane pressures are from 20 to 1,000 kPa (0.2 to 10 bar), and usually in the range 100 to 300 kPa. Again, in special applications like membrane an MBR, vacuum in the range of up to 0.2 bar is applied.

3.3 Nanofiltration (NF): the membranes used in NF operate on a solution diffusion principle, diffusing monovalent ions through the membrane, rather than blocking material from passing through the membrane due to pore size like MF or UF. NF is useful for colour removal, sugar and dye removal or for removing THM (trihalomethane) pre-cursers and hardness or sulphate from a water supply. Together with operation possibilities at low pH values it is also ideally applied to the purification of acid mine drainage (AMD). In combination with seeding technology and hydrocyclone classification it is possible to achieve a permeate recovery of up to 95 % from highly concentrated landfill leachate /10/. Transmembrane pressure is up to 5,000 kPa (50 bar), and usually in the range 1,500 to 2,000 kPa.

3.4 Reverse osmosis (RO): RO osmosis is operated with the tightest membrane types available. The organic and inorganic molecules are separated from the feed solution by a solution diffusion process with a rejection rate in the range of up to 99%. Typically, RO membranes are used to separate aqueous salts and ions with less than 200 D, where a Dalton (Da) is numerically equivalent to the molecular weight in g/mol. Applications range from ultrapure water for semiconductor and pharmaceutical use to desalination of seawater for drinking water production, and the purification of industrial waste water, like landfill leachate. Operating pressure for RO is usually up to 7,000 kPa (70 bar), for low pressure RO up to 1,500 kPa and for high pressure RO up to 15,000 kPa (150 bar).

4. Operational cluster of membrane plants

While approved and well known technical solutions are usually available for the design and the manufacture of a membrane based unit, pre-treatment of the water to be processed, as well as the handling of the retentate and the different waste water streams produced during operation of a membrane plant, have to be adapted case-by-case to the specific conditions at the construction site of a plant. These can differ over a wide range, since apart from the influences determining the raw water quality, the details related to infrastructure as well as logistics, are usually very different, and consequently, have to be considered during the design, construction and operation of each membrane plant /4/.

The above considerations include the systems for dosing and handling of agents for pre-treatment, agents needed during operation, agents for the cleaning of membranes, and, in addition, the treatment and discharge of the diverse waste water streams generated during these specific activities. A flow sheet has been developed for the specification and evaluation of the correlated interdependencies (Figure 2) which summarizes the main operational cluster of a membrane plant, here specified by way of example for a seawater desalination plant with RO. The term ICT refers to “Information and Communication Technology”, which is the basis for an efficient SCADA (Supervisory Control and Data Acquisition) system including remote control and data handling /11/.

5. Selected example for future applications

A large number of scientific institutions, industrial enterprises, water suppliers and wastewater boards have participated in the development and application of membrane technology, partially supported by governmental R&D funds. This has been the case in the past, is valid for the current situation, and can be foreseen for the future development.

In Germany, for example, membrane technology today represents a proven alternative to the classical processes of municipal and industrial waste water treatment. This pays off in terms of ecology and economy because the usage of membrane technology means fewer costs for water supply and wastewater disposal as well as industrial production, and also results in significantly less environmental stress /1, 12/.

Beside the many conventional solutions in water management based on membrane processes that have been realized in the past and are actually implemented, more innovative solutions can be expected. Two solutions, that are considered to become increasingly important in related niche applications, are:
a) NF for the decentralised production of safe drinking water from contaminated surface waters
b) UF and RO in combination with other treatment steps to achieve a ZLD process for the treatment of brackish water in arid and semi-arid areas.

5.1 Nanofiltration for decentralised production of safe drinking water

The supply of clean potable water is, in the meantime, acknowledged as a basic human right. In semi-arid areas, and countries in tropical as well as sub-tropical climate zones, there is, in principle, enough water available from surface waters. However, often, and due to a high burden of polluting matter from extremely health damaging components, this water cannot, or shall not, be used as drinking water /13/.

Thereby, the kind of contamination of surface waters can be very different. The spectrum ranges from microorganisms including algae, bacteria, parasites as well as viruses, and alarming harmful organic micro pollutants, over contamination with chemicals and diverse poison residua from industry and agriculture up to particles and suspended solids of organic or inorganic origin. Related water treatment plants or units have to be adapted to the requirements existing on site. In the case of a centralised drinking water supply usually large-scale plants are installed. For the production of drinking water from seawater by RO, plants typically have a production capacity in the range of 50,000 to 100,000 m³ per day, with single cases up to 500,000 m³/day. Adjusted to the conditions required of a decentralised potable water supply, smaller or small units with a production of potable water of a few m³ per day down to few hundred litres per day are available, especially for disaster and emergency situations /14/.

In connection with the decentralised supply of (only) drinking water, a compact unit designed for robust operating conditions is considered to be a very promising solution (Figure 3); this is a membrane module equipped with a NF membrane /15/. The peculiarity is the membrane element itself which is designed according to the open channel construction that is used very successfully worldwide and has also proven to be suitable for other applications in water treatment /16/.

Based on the usual conditions concerning temperature and contamination of the raw water to be treated, at about 5 bar operating pressure a permeate production of up to 1,500 litres per day can be achieved. With a power demand of about 250 W at these conditions, for the supply of the electrical energy necessary for the operation of the unit even the use of, for example, photovoltaics is possible. Such an approach allows the unit to be particularly used for the production of drinking water in emergency or disaster situations where the whole infrastructure has been destroyed, for instance, after a tsunami. Alternatively, it can be used for initiatives which aim to “help people to help themselves” in remote areas with no clean water resources, or even addressing “microbusiness in selling drinking water” in (for example) 10 liter bottles.
5.2 Multistep Zero Liquid Discharge (ZLD) process

Adapted to the special demand in arid and semi-arid areas with very limited access to water of good quality, but availability of wells with brackish water, a combination of UF and RO for the purification of usually complex and difficult to treat water has been developed and operated successfully /17/. For this concept, different processes with diverse driving forces for the treatment of the retentate are integrated which allows for a high recovery rate for the different main water streams as basis for a ZLD approach /18, 19/.

6. Future Development of Membrane Technology

At present, important developments are taking place in industrial membrane applications focused on the integration of different membrane processes in thermal separation technology and chemical or biological transformation. Bearing these in mind, better product quality, highly compact production plants and processes with improved efficiency, reduced energy consumption and sustainable environmentally friendly operation can be achieved /5 - 7/.

The future development of membrane technology will be influenced by factors such as /5 - 7/:
- A reduction in treatment costs because of increasing operational experience and longer membrane life time.
- The production of membranes adapted to specific applications.
- Increased efforts to reduce biofouling on the membrane surface.
- Increased efforts to develop and optimize processes, e. g. forward osmosis and membrane based processes focussed on ZLD.
- Reliable process monitoring.
- Reliable discharge control.
- Standard plant concepts with easy adaptation to each individual situation on site.
- Realisation of "plug & play" concepts.
- Broader use of Build-Own-Operate or Build-Operate-Transfer agreements.
- Integration of membrane technology in a total water management based on "graduated quality requirements".

All in all, described here by way of example for seawater desalination with RO, improved membrane technology related aspects will contribute to lower the specific energy demand, and thus to reduce the carbon footprint. This includes, for example, RO membranes with higher specific permeate flux and/or higher salt rejection, as well as pumps and energy recovery devices or energy saving systems with higher efficiency.

However, of the same importance are improved and environmentally sound systems for seawater intake and partial pre-treatment, that avoid the negative impact of the operation of seawater RO desalination plants on the environment and reduce overall operating costs. So, for example, sub-seaied drains allow operation that is independent from the growing number of natural disaster scenarios such as algae bloom, that are causing increasingly problems in this area of water treatment /20/.

Similar strategies will also improve the integration of MF, UF and NF.

7. Conclusions

The need for clean and affordable water for an increasing population on the one hand, escalating energy costs and water scarcity, overstressing and/or contamination of the natural resources in many areas of this world, on the other, are the most important driving forces for the increasing demand for improved technology for water and wastewater treatment or purification. In this regard, membrane technology has been used, is used and will be used successfully, and increasingly, for different purposes and for a wide range of applications within the area of treatment and purification of water and wastewater.

Such an evolution is based on features including compactness of the plants, short construction time, clean, easy, economical and long term reliable operation with high rejection rates of components/contaminants. The high operational performance is achieved mainly due to the barrier function of the membranes, but is also based on the experience gained in the last decades and the improvements in material selection for the manufacture of the membranes and the plants, as well as the increasing optimisation of operational aspects including capacity building and preventive maintenance.

Literature:
/3/ Peters, Th.: Modern Water and Waste Water Purification, Structural Change in Europe, Hogrefe Publications, Böblingen, Germany, June 2000
/4/ Peters, Th.: Desalination of sea water and brackish water with reverse osmosis and disc tube module DT. Proceedings WSTA Forti Gulf Water Conference, Bahrain, 13-18/02/1999
/7/ Macedonio, F., Drioli, E.: Membrane engineering progresses in desalination and water reuse. Membrane Water Treatment, 2010, 1 (1), 75
/9/ Peters, Th.: Reduzierung des Nitrathaltiges im Trinkwasser mit Umkehrosmose [Reduction of the nitrate content in drinking water with reverse osmosis]. WASSERNATURSCHAFT, 10/03
/10/ Peters, Th.: Purification of industrial waste water by separation of sulphate using nanofiltration and seeding technology. Proceedings, ACHHEMA 2012, Frankfurt a. M., Germany
/11/ Peters, Th., Pinto, D.: Seawater Intake and Pre- treatment Using Neodren Technology Based on Sub- Seabed Drains. Proceedings, IDA World Congress on Desalination and Water Reuse. Mispalomas, Gran Canaria, Spain, October 2007
/12/ Peters, Th., Gunther, R., Vossegou, K.: Membrane bioreactors in wastewater treatment. Filtration + Separation, January/February 2000
/13/ Peters, Th.: Safe Drinking Water Abstraction from Surface Waters. Arab Water World, 10/2013
/14/ A Najib. B., Bundesanstalt Technisches Hilfswerk [German Federal Agency for Technical Relief], personal communication, Bonn, April 2014
/15/ ROCHEM Technical Services, company brochure, Hamburg, 2013
/17/ E. Marathy, N., personal communication, Cairo and Oman, October 2014
/18/ Peters, Th.: Visit and inspection of the AGRO-ZLD system from INTERNATIONAL DESALINATION & WATER TREATMENT GROUP. Internal report, Neuss, October 2014
/19/ Peters, Th.: Improving the Performance of Seawater Desalination Technology by Using an Optimized Intake System and Recovering Valuable Components from the Brine. Presentation at BT’s 2nd Annual World Congress of Ocean – 2013, Hangzhou, China, 23-25 September 2013
/20/ Peters, Th.: Improving seawater desalination with reverse osmosis. FILTRATION, 8 (4), 2008