Industrial Water Desalination by Vacuum Multi-Effect Membrane Distillation

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Water shortage and a rising water demand are prevalent issues on the political agenda worldwide. Available water resources must not only be provided to ensure a domestic and drinking water supply for a steadily increasing population but also for the growing industrial and agricultural sectors. This work outlines how the use of the innovative vacuum multi-effect membrane distillation contributes to improve the water management efficiency in the following key industry sectors: desalination, drinking water and beverage industry, pharmaceutical, agro and chemical as well as oil and gas industry.

Keywords: Desalination, Industrial water management, Vacuum multi-effect membrane distillation, Water reuse

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1 Water Demand in Important Sectors and Industries

During the United Nations Sustainable Development Summit held from September 25–27, 2015 in New York, the General Assembly adopted the 2030 Agenda and agreed on the universal goal to ensure the availability and sustainable management of water and sanitation for all. By 2030, the universal and equitable access to safe and affordable drinking water for all and the substantially increase of water-use efficiency across all sectors should be achieved [1].

To reach these goals, the international cooperation has to be expanded and capacity-building support for developing countries in water-related activities and programs, including water desalination, water efficiency, wastewater treatment, recycling and reuse technologies, has to be provided. However, these objectives cannot be achieved without suitable process technologies developed by technology-driven companies applying an adequate business model. Private sector activities, investments, creativity, and innovation are the major instruments to solve the sustainable development challenges [2].

Due to their main application for the production of drinking water or fresh water for industrial processing as well as within water reuse concepts, water and seawater desalination technologies are the key factors for the development and ongoing operation of the industrial manufacturing. The Middle East and North Africa (MENA) is an important region in direct neighborhood to Europe suffering from a great water scarcity [3, 4]. Hence, it is an illustrative example for the importance of water desalination and wastewater reuse for a sustainable local industry.

One relevant and new development to provide a sufficient water supply by economically and ecologically suitable technologies is the vacuum multi-effect membrane distillation (VMEMD). In the following, this technology is described, and the main fields of its application are presented.

2 Technology of VMEMD

The two main process steps to purify salty water are membrane filtration and evaporation. The VMEMD is an advanced technology that combines the benefits of the thermal multi-effect distillation and the membrane filtration step: at first, water is separated from its pollutants by evaporation and the produced steam is filtered by a microporous, hydrophobic, steam-permeable membrane made of polytetrafluoroethylene (PTFE).

The membrane consists of a stretched PTFE layer on a polypropylene (PP) backing structure (Fig. 1). It rejects liquid water due to its nonpolar surface properties, whereas steam can pass the membrane pores. Typical pore sizes are between 0.1 and 0.5 µm. Any solved solids (salts, hardness) as well as particles, bacteria, endotoxins, and high-molecular-weight natural organics in the feed water are nonvolatile. Small drops are also rejected by the membrane and remain in the concentrate. A subsequent condensation of the steam creates premium pure water.

An exemplary scheme of a VMEMD process with three effects is shown in Fig. 2. Primary steam is used to heat the feed stream that enters the first effect stage (Fig. 1, left side). The feed stream partly evaporates and passes the membrane in gaseous form. In case of saltwater, water is evaporated,

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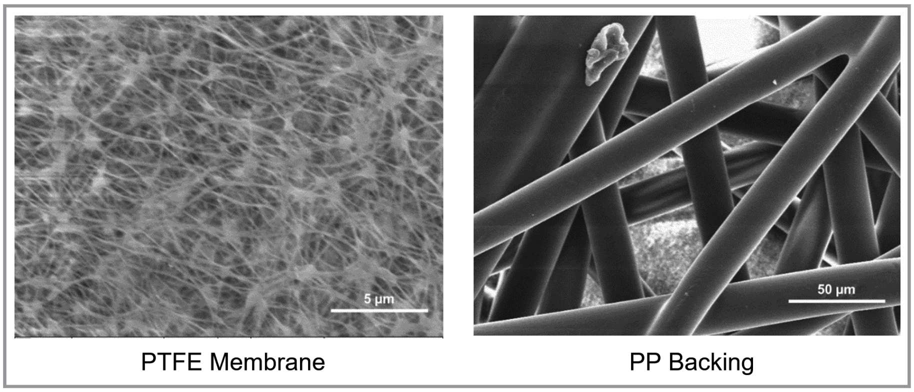

Figure 1. Scanning electron microscope (SEM) images of the microporous VMEMD membrane and its backing.

condensed, and gathered as pure distillate, whereas the salt remains in the liquid stream resulting in a concentration of the feed solution.

The generated steam is passed to thin foils that are part of the following effect where the condensation occurs. The condensation heat is recovered and heats up the feed stream again. Pressure and temperature are decreasing from effect to effect, the evaporation takes place again at a respectively lower pressure and temperature. The final steam is condensed in a separate condenser, which is indirectly cooled, e.g., by raw water or free air cooling.

This way of cascading effect stages can be repeated up to ten times. The recovery of the evaporation heat leads to a very energy-efficient process in terms of heat supply. Owing to a typical maximum temperature of the heat source of only 90 °C, solar energy or waste heat can easily be used to run the process. Besides thermal energy, VMEMD only requires a small amount of auxiliary electrical energy for its controlling, pumps, sensors, and valves.

The basic element of the membrane module provided by EvCon GmbH, which is exemplarily represented herein, is a polymer-based frame (Fig. 3), which is either equipped with the microporous membrane or with the condensing foil made of PP. Frames equipped with the membrane form the evaporation channels and frames equipped with foils form the condensation channels. Membrane and foil frames are alternately arranged, which leads to feed water channels in between that are formed by a condensation foil and an adjacent membrane. The frames are stacked and welded to blocks. Several blocks form a module.

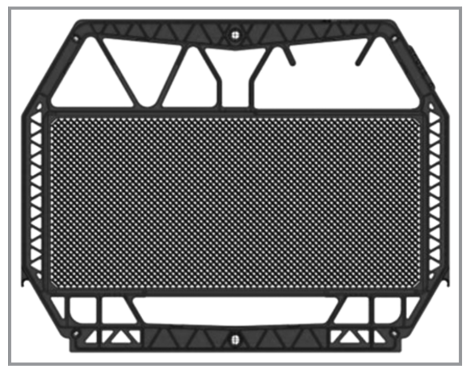

Figure 3. Polymer-based frame of the VMEMD module.

One of the main challenges, which significantly impedes the industrial implementation of membrane distillation in general, is to avoid the so-called wetting of the hydrophobic membrane [5]. If wetting occurs, the membrane turns hydrophilic and liquid water can pass the pores. Wetting can be caused by contaminants in the feed solution, e.g., surfactants, or by an inhomogeneous flow pattern in the

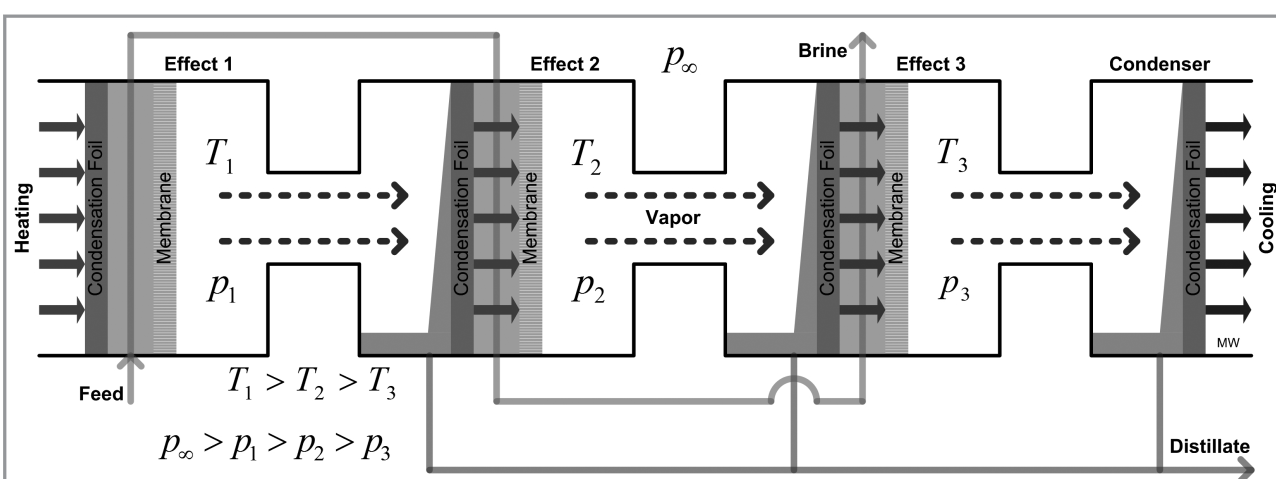

Figure 2. Scheme of the VMEMD process.

feed channel, which can locally lead to oversaturation and therefore crystallization. In other membrane distillation modules, designed as direct-contact systems, membrane wetting results in a contamination of the produced water as the untreated feed solution directly enters the liquid permeate being in contact with the membrane backing surface.

In the third generation of the VMEMD system, the flow pattern in the feed channel is highly uniform and, thus, reduces concentration polarization effects. If wetting phenomena should yet occur for some other reason, a contamination of the product water is prevented due to the special design of the steam channels. Any liquid passing through the membrane is drained to the bottom of the membrane frame and conducted out of the system.

Another great advantage of the VMEMD system is the possibility to hydrophobilize the membrane in situ in case of unexpected wetting. This means that wetted membranes can be recovered. Due to a construction consisting only of corrosion-resistant polymers without the use of adhesives, detergents with high pH values can be used to remove strong contaminations.

3 Applications for the VMEMD Process

The VMEMD process can be used in a wide range of applications. Due to its special design, the process can beneficially be applied for ultrapure (UP) water applications like in the pharmaceutical industry or for the production of makeup water for process steam. Beyond that, the process can be used for high-concentration tasks aiming to gain high recovery rates close to saturation concentration. Typical applications are the recovery of reverse osmosis (RO) brines to increase the overall recovery rate, sea water and brackish water desalination, and the concentration of sugar solutions. The typical size of one VMEMD system ranges from a distillate capacity of 100 to 2000 m^3d^{-1}. The rack-and-stack module configuration enables a combination of several systems and, hence, the operation of huge membrane areas.

3.1 Desalination

Due to population growth, climate change, and urbanization, water deficiency will continuously get worse. In addition, there is increasing dry land salinity in coastal areas. According to prognoses of the World Resources Institute (WRI), 33 countries could already suffer from an extreme lack of water by 2040 [2]. In this context, desalination technologies play a steadily increasing role in securing the worldwide potable water supply.

It is expected that, due to rapid industrialization, increasing population, and depleting freshwater bodies, the global water desalination market will reach a value of 26.81 billion USD by 2025. Moreover, global warming has eventually already resulted in an accelerated evaporation of water bodies as well as a higher incidence of droughts in numerous parts of the world. The largest revenue share is accounted for by seawater desalination in 2016 (up to 58.2 %). This trend is assumed to continue, as a rapid industrialization and substantial investments for desalination plants in the next few years are the forecast for the Middle East [6].

However, conventional processes like seawater reverse osmosis (SWRO) are recently reaching their limits. Local circumstances are responsible for a considerably elevated salt content in the ground water. The treatment of saline water by pressure-driven technologies such as RO is limited due to the osmotic pressure. Conventional thermal processes like multi-stage flash distillation (MSF), on the other hand, depend on mid-temperature heat, e.g., from nearby power plants, and therefore, are competing with water for power generation. Multi-effect distillation with thermal vapor compression (MED-TVC) mainly needs electrical power like RO.

3.1.1 Technology Comparison

All the above-mentioned methods are limited with regard to their yield of fresh water. For that reason, companies are extensively investing in R&D to enhance desalination technologies. For instance, in April 2014, GE Corporation launched an open technology challenge to accelerate the developments concerning the efficiency of seawater desalination [7]. In Tab. 1, the state-of-the-art typical operational parameters for the main seawater desalination processes are compared to the values gained by VMEMD.

Of course, the main factor is the achievable water quality. As the produced vapor in the VMEMD process has to pass

Table 1. Typical operational parameters for the main seawater desalination processes.

Parameter	MSF	MED-TVC	SWRO	VMEMD
TDS in concentrate [%]	ca. 5.8	ca. 5.0	ca. 6.4	ca. 6.4[a)]
Typical seawater recovery [%]	ca. 40	ca. 30	ca. 45	ca. 45[a)]
Typical TDS in product water [mg L^{-1}]	< 25	< 25	250–500	< 10
Max. concentrate temperature [°C]	< 115–120	< 70	< 45	< 85
Typical heat source [°C]	steam 2.5–3 bar	steam 2.5–3 bar	none	hot water or low-pressure steam

Data based on a total dissolved solid (TDS) value for seawater of 3.5 %. a) Limited by scaling, e.g., $CaSO_4$.

a microporous membrane, small droplets cannot contaminate the product water, which is why the reached water quality is better than with the standard thermal processes (Fig. 4). Furthermore, the VMEMD water quality is far better than the RO permeate. It also has to be mentioned that due to the limited drinking water concentration of boron, RO plants are often constructed as a two-pass system, in which the permeate of the first stage, or a certain part of it, is treated by a second one.

Important cost factors are the recovery rate and of course the energy demand or carbon footprint. The recovery rate is the ratio between the desalted water and the feed water flow rate. A low recovery rate means a higher feed water consumption resulting in higher investment and operating costs for the water intake as well as the discharge and pretreatment systems. The recovery rate of RO is limited by the osmotic pressure, for VMEMD it is limited by scaling. VMEMD allows at least the same recovery rate than the RO process.

An advantage of the RO process is the relatively low energy consumption compared to the standard thermal processes for brackish as well as seawater applications. Whereas only electricity is needed for RO operation, the standard thermal processes need thermal energy and electricity. Therefore, the pressure-driven RO often remains the preferred technology if no usable waste heat is available or special claims concerning the product quality have to be considered.

Except for a small amount of electrical energy for pumps and process control, the VMEMD process only needs low-temperature heat and could easily be operated with solar energy. The main reason for the high capital costs for standard thermal processes compared to RO is the need to use high-quality stainless steel or similar metals like brass or titanium for plant constructions. But even if the high material requirements are met, corrosion is still not completely avoidable, just like the emission of copper and nickel. Consequently, the operation costs for a standard thermal desalination always suffer from corrosion damages. In case of VMEMD though, the entire plant is made from completely corrosion-resistant plastics resulting in lower investment costs as well as lower emission of heavy metals into the environment.

3.1.2 Desalination with VMEMD

The quality of a desalination process is often measured in terms of the salt rejection rate R:

$$R = 1 - \frac{c_P}{c_F} \tag{1}$$

with the permeate concentration c_P and the feed concentration c_F. A typical value for the rejection rate in sea water desalination is > 99.5 %.

The ratio between the concentration of a contaminant in the product water c_P and its concentration in the feed water c_F is defined as the decontamination factor DF:

$$DF = \frac{c_P}{c_F} \tag{2}$$

Fig. 4 presents the results of a test run with the VMEMD system with a feed water containing 20 wt % NaCl (conductivity: 228 mS cm^{-1}). Over the first test period of more than 180 days, the conductivity of the distillate remains less than 10 µS cm^{-1}. This corresponds to a rejection rate of more than 99.99 % or a decontamination factor of $2.2 \cdot 10^{-5}$. In comparison, the decontamination factor of RO is $4.0 \cdot 10^{-3}$.

These values show the quality of the water produced by the VMEMD separation process. Furthermore, the results of this long-term test run prove that the carefully designed feed channels enable a uniform velocity of the feed flow

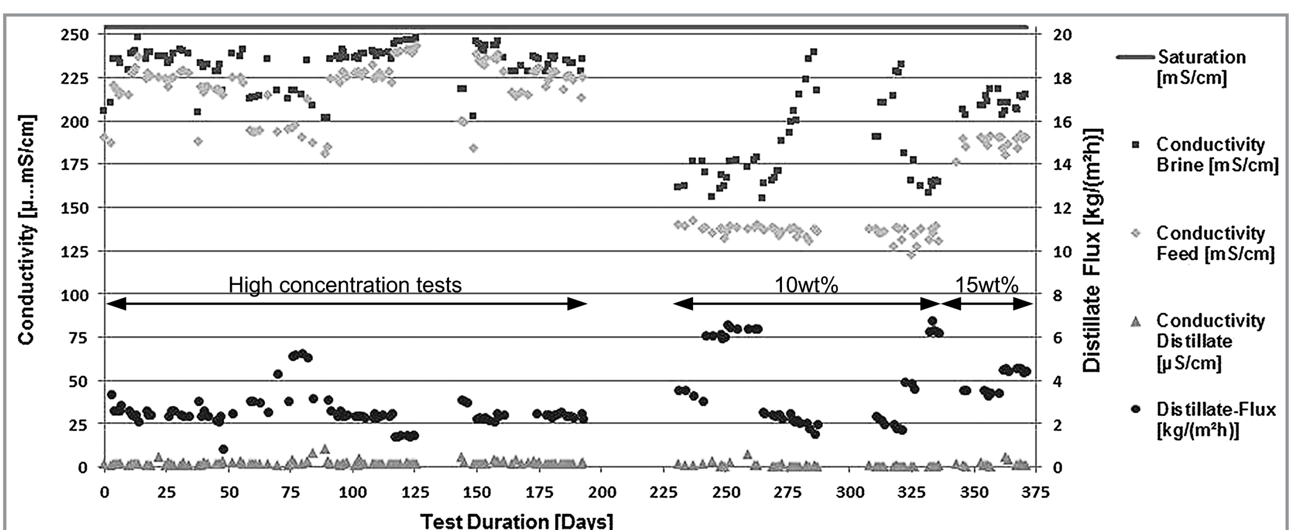

Figure 4. VMEMD long-term test run with highly concentrated salt solution.

across the membrane surface. Therefore, the concentration polarization is kept to a minimum, which avoids wetting of the hydrophobic membrane.

3.2 Drinking Water and Beverage Industry

Fig. 5 shows the development of the global market for bottled water and its regional split [8]. It is expected that the global bottled market volume will increase by 30 % in the next four years. One third of this market volume is realized in Europe and Middle East and Africa. The basis for a good quality of produced beverages is UP fresh water, independent of its source and production location. The VMEMD system allows a production of high-quality water in a one-step process, which is an appealing factor for the beverage industry.

In addition to the quality parameters regarding the drinking water production mentioned in Sect. 3.1, the microbial quality of the water is an important issue in the beverage industry. It has long been proven that RO membranes constitute an excellent barrier to microorganisms. RO membranes are able to reject bacteria, larger pathogens, and almost all viruses [9–11]. High-quality RO processes are suitable treatment steps to remove pathogens, but they have to be properly selected and maintained [12].

The level of the removal of microbial contaminants by an RO process varies significantly, as it is a function of the membrane itself and, even more, the technical perfection of the entire system down to the last detail, such as seals. Adham et al. [13] reported removals ranging from 2.7 to more than 6.8 logs for different RO systems.

In standard thermal processes used for desalination, microbial inactivation is controlled by the applied temperature profile and the duration of the water remaining at a certain temperature level. A safe inactivation of vegetative cells in a humid atmosphere occurs at temperatures ranging from 50 to 60 °C maintained for a period of 5 to 30 min. More resistant are spores, endospores, and other resistant forms. A thermal short-term treatment at temperatures of 72 °C for a period of 15 s leads to an inactivation of most vegetative pathogens [3].

By distillation at high temperatures close to the boiling point of water at standard ambient conditions, substantially all pathogens are eliminated. A multi-stage system, however, partly operates at reduced pressures and corresponding lower temperatures of 50 to 60 °C. Several pathogenic organisms are denatured or inactivated in a few seconds to minutes at temperatures between 60 to 80 °C. Spores and some viruses usually require higher temperatures in the range of 70 to 100 °C and a longer time period to be inactivated [3]. For this reason, a contamination of the product water by small droplets containing inactivated pathogenic organisms like spores and viruses cannot be excluded.

In a VMEMD system, the produced vapor has to pass the microporous hydrophobic membrane with a pore size of 0.1–0.5 µm, which provides an additional barrier to microorganisms. For example, *Giardia cysts* can vary from 4 to 14 µm in length and 5 to 10 µm in width, *Cryptosporidium oocysts* range from about 4 to 6 µm.

In addition to the production of ultrapure water, the VMEMD system can also be used to concentrate fruit juices or natural aromas. By specifically selecting the evaporation temperature, it is possible to preserve flavors and taste. The hydrophobic membrane also has a positive effect on aromas and flavors in the concentrate.

In the beverage industry, the advantages of the VMEMD technology ensure a particularly high process security. Due to the high recovery, the process also allows a reduction of water disposal during the production of UP water to a minimum. Resulting from the possibility to partly operate the system, VMEMD offers a high flexibility in terms of the adjustment to current requirements. The opportunity to use waste heat from surrounded processes within the beverage production to run the VMEMD system is another beneficial option.

3.3 Pharmaceutical Industry

The aim in this business sector is to produce water with the highest quality and reliability standards. The methods for producing purified water (PW) or water for injection (WFI)

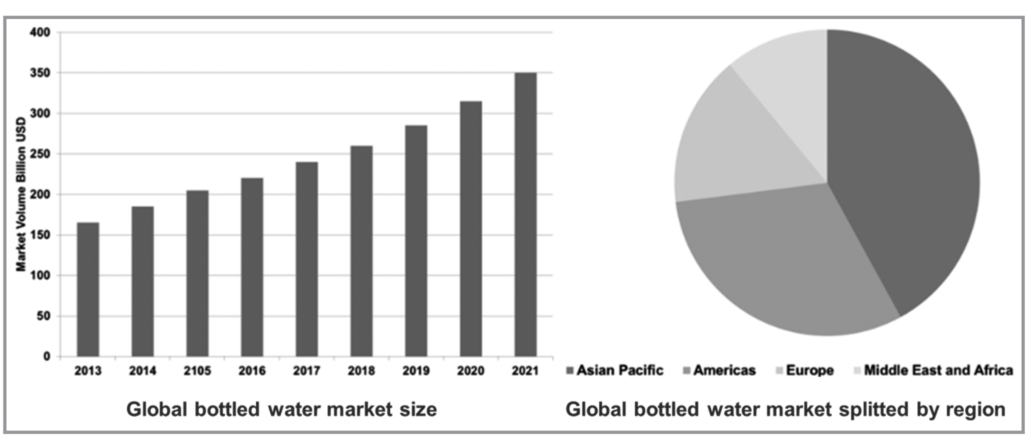

Figure 5. Global bottled water market. Data taken from the Business Research Company [8].

are strongly regulated in the respected pharmacopeias. Tab. 2 shows an excerpt from experimental data obtained with a VMEMD process to produce pharmaceutical water compared to the official requirements. The data clearly demonstrate that all relevant parameters of the water produced by the innovative VMEMD system are far below the required standard limit values.

Table 2. Excerpt from experimental values of VMEMD compared to WFI requirements. CFU, colony-forming unit; EU, endotoxin unit.

Parameter	VMEMD process	Requirements [14]
Conductivity [$\mu S\,cm^{-1}$]	0.5–0.8	< 1.3 (20 °C)
Bioburden [CFU (100 mL)$^{-1}$]	< 1	< 10
Endotoxins [EU mL^{-1}]	< 0.05	0.25
Nitrates [ppb]	< 50	< 500

Fig. 6 compares the typical process to prepare high-quality WFI to the one-step VMEMD method. The state-of-the-art process to achieve the necessary purity is a multi-step treating process. PW production includes chlorination, softening, activated carbon filtration (dechlorination), RO, and ultraviolet disinfection. To reach the requirements for WFI, additional multi-effect distillation steps and an ultrafiltration step are necessary.

The innovative VMEMD enables a very reliable as well as energy- and cost-efficient UP water production for pharmaceutical purposes in a one-step process for the first time. Due to a separation caused by phase change and a simultaneous filtration across a microporous membrane, the VMEMD system ensures the production of excellent-quality PW for pharmaceutical applications as well as WFI that fulfills the strict regulatory requirements worldwide (see also Sect. 3.2). As an example, Fig. 7 shows a VMEMD plant with a membrane area of 1200 m^2 and an UP water production capacity of 6000 L h^{-1}.

Figure 7. VMEMD plant with a membrane area of 1200 m^2 and an UP water production capacity of 6000 L h^{-1}.

3.4 Agro-Industry

The advanced agro-industry and agriculture need pure water in reproducible quality. The usage of water includes the irrigation of fields and greenhouses, but also the application as process water, e.g., in sugar mills. In 2007, Eurofresh Farms in Willcox, Arizona, USA, sold more than 90 000 t of hydroponically and pesticide-free grown tomatoes [15]. Eurofresh owns 1.29 km^2 cultivated glass-covered area and represents about one third of the commercial hydroponic greenhouse area in the USA [16]. As of 2017, Canada had hundreds of large-scale commercial hydroponic greenhouses, producing tomatoes, peppers, and cucumbers [17]. Due to technologi-

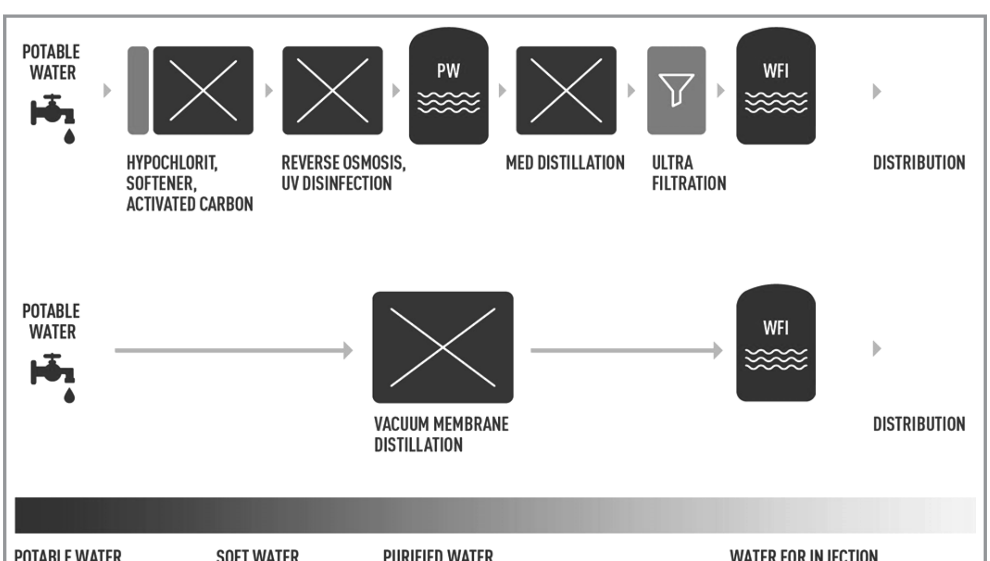

Figure 6. Standard process vs VMEMD process.

cal advancements within the industry and numerous economic factors, the global hydroponics market is forecasted to grow from 226.45 million USD in 2016 to 724.87 million USD by 2023 [18].

A very innovative cultivation practice in the agro-industry is the so-called hydroponic system, in which the plants grow without soil, but with their roots exposed to water [19]. In a typical continuous-flow solution culture, water with a precisely added mineral nutrient constantly flows around the roots. These systems are fully automated and temperature, pH, and nutrient concentrations are controlled.

Hydroponic systems could be an excellent way for food production as Tab. 3 impressively shows [20–23]. This applies particularly for areas that are not suitable for common agriculture and water resources. Hydroponic systems only consume 10 to 20 % of the water needed for an equal amount of field-grown plants, due to the lack of water loss by evaporation from the soil. Furthermore, hydroponic systems offer a very high efficiency of nutrient use, as only the amount of the actual plant uptake has to be replaced in the circulating nutrient solution.

Although hydroponic systems have many benefits, there is a need to pay special attention to the water supply and the wastewater reuse, because water-borne diseases can contaminate and spread through the water tubing systems. Common plant pathogens detected in hydroponic systems are species of *Colletotrichum, Fusarium, Phytophthora, Pythium*, and *Phizoctonia* [25–28].

The standard methods to inactivate the growth of pathogens apply high doses of ultraviolet and gamma irradiation. A more environmentally friendly approach is to install a water purification system that produces high-quality and microorganism-free water. It is pretty obvious that VMEMD is a highly appropriate process, not only for the purpose of producing make-up water but also with regard to wastewater management and water reuse.

To keep the nutrition solution on a high hygienic level, a partial stream of the circulating water is constantly removed from the water cycle and sanitized. Since this stream contains mineral nutrients as valuable substances and cannot harmlessly be discharged into the environment, a suitable downstream processing can significantly optimize the overall efficiency of the system. With a VMEMD process, the wastewater of a hydroponic system can even be treated profitably, since the concentrated nutrients as well as the separated water can be recycled. The required sanitizing effect coincidently occurs due to the high temperature level and the microfiltration of the vapor during the process.

Table 3. Quantity of crop (hydroponic vs soil culture) [24].

Crop	Hydroponic	Soil Culture
Wheat [$kg\,ha^{-1}$]	5600	670
Oats [$kg\,ha^{-1}$]	3360	950
Rice [$kg\,ha^{-1}$]	13 450	840–1010
Maize [$kg\,ha^{-1}$]	8970	1680
Soybean [$kg\,ha^{-1}$]	1680	670
Potato [$kg\,ha^{-1}$]	78 450	8970
Beet root [$kg\,ha^{-1}$]	22 420	10 090
Cabbage [$kg\,ha^{-1}$]	20 170	14 570
Peas [$kg\,ha^{-1}$]	15 690	2240
Tomato [$kg\,ha^{-1}$]	201 750	5600–11 210
Cauliflower [$kg\,ha^{-1}$]	33 620	11 200–16 800
Lettuce [$kg\,ha^{-1}$]	23 530	10 090
Lady's finger [$kg\,ha^{-1}$]	21 300	5600–8970
Cucumber [$kg\,ha^{-1}$]	31 380	7850

3.5 Chemical Industry

In the chemical industry, the following fields of application arise for the VMEMD process: reclamation and reuse of water, reclamation or concentration of high-value or reusable components, closing of production cycles, and reduction of wastewater streams aiming a zero-liquid discharge (ZLD).

As an example for the capability of the VMEMD system to run under very tough conditions, a ZLD approach for waste pickling liquors (WPLs) and the recovery of iron-(II)-chlorides ($FeCl_2$) are described. Pickling liquors from steel-refining plants are highly acidic and salty wastewaters. The used acid bath solutions are primarily contaminated with $FeCl_2$ and small amounts of hydrochloric acid. The current state of the art describes the concentration of WPL up to crystallization for the recovery of $FeCl_2$ as an expensive and complex undertaking. Here, the main problem is the highly corrosive behavior of the WPL. The VMEMD system can overcome the corrosion problem, because only polymer materials such as PP are used.

In a VMEMD pilot plant, the treatment of a WPL has successfully been proved. The WPL was heated up to a temperature of 80 °C and a brine with a $FeCl_2$ concentration close to saturation could be achieved. Because the solubility of iron chlorides decreases with decreasing temperatures, $FeCl_2$ crystals are formed directly after the VMEMD process in a downstream crystallizer (Fig. 8).

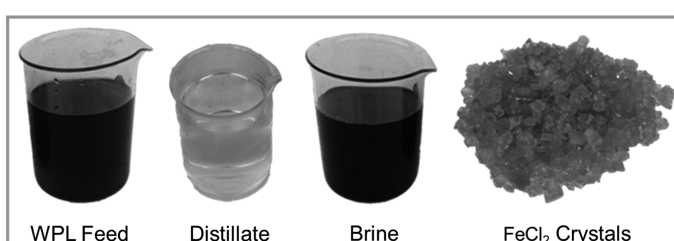

Figure 8. WPL feed, distillate, brine, and $FeCl_2$ crystals.

3.6 Oil and Gas Industry

Many new extraction methods to exploit oil and gas resources from shale, oil sands, tight gas resources, or coal-bed methane sites consume considerable amounts of water to enhance the oil and gas recovery. Hydraulic fracturing is one of the most commonly used methods, but the coproduced wastewater carries large amounts of salt, which is formerly present as rock salt in the exploited caverns or added as process chemical. New technologies for the treatment of such wastewaters are required to enable onsite water recycling and reuse as well as a wastewater concentration up to saturation to reduce the amount of wastewater that is injected underground.

After separation of oily and sandy components by existing methods like induced gas flotation or hydrocyclones, the remaining highly saline waters (more than 100 000 ppm) require new technical approaches. VMEMD technology can be a suitable option to fill this gap. Since the salt content is way too high for an RO process, an evaporation step is necessary. As not only corrosion-resistant materials but also high energy efficiency are requested, an application of VMEMD seems to be an appropriate choice.

Pilot trials with a commercial VMEMD water treatment system in Texas, USA, showed the following parameters during continuous operation: distillate flux of $5\,\mathrm{kg\,m^{-2}h^{-1}}$, distillate conductivity constantly $< 600\,\mu\mathrm{S\,cm^{-1}}$, uptime of more than 90 %, at least 90 % performance recovery after any required clean-in-place procedure, and achievable concentrate salinity of 24 wt % NaCl.

4 Conclusions

This study indicates that VMEMD is a disruptive technology with regard to various industrial desalination challenges. It is a prospective technological solution for a sustainable treatment of process waters in some of the key sectors like desalination, drinking water and beverage industry, pharmaceutical, agro- and chemical industry as well as oil and gas industry. With the particular advantages it offers, demanding tasks concerning water demand can be solved in an energetically favorable way, whereas unfavorable processes can be replaced.

The VMEMD system in its third module generation accomplished a technological leap in development due to a doubling of membrane area, an improved flow control and a more efficient production process of the modules. VMEMD is an innovative process that can play an important role to realize the universal and equitable access to safe and affordable drinking water for all and a substantial increase of water use efficiency across various important sectors in industry. Every effort should be made to put this forward-looking technology into industrial practice.

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Christine Kleffner holds a Diploma and a Master's degree in Process Engineering and Plant Design. Researching in the field of membrane technology for industrial water treatment, she is doing her PhD at the TH Köln in cooperation with the TU Kaiserslautern. Her main working fields are high-pressure reverse osmosis, nanofiltration and membrane distillation with regard to water reuse and the concentration of salt solutions with high osmotic pressures. She is a freelance lecturer for technical thermodynamics.

Symbols used

c_F	$[\mathrm{g\,L^{-1}}]$	feed concentration
c_P	$[\mathrm{g\,L^{-1}}]$	permeate or product water concentration
DF	[–]	decontamination factor
R	[–]	rejection rate

Abbreviations

CFU	colony-forming unit
EU	endotoxin unit
MED-TVC	multi-effect distillation with thermal vapor compression
MSF	multi-stage flash distillation
PP	polypropylene
PTFE	polytetrafluoroethylene
PW	purified water
RO	reverse osmosis
SEM	scanning electron microscope
SWRO	sea water reverse osmosis
TDS	total dissolved solids
UP	ultrapure
VMEMD	vacuum multi-effect membrane distillation
WFI	water for injection
WPL	waste pickling liquors
ZLD	zero liquid discharge

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