European Roadmap of Process Intensification

-Technology Report –

Technology: ***Membrane Distillation Technology***

Technology Code:

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1. Technology

1.1 Description of technology/working principle

(feel free to modify/extend the short technology description below)

Membrane distillation (MD) is a relatively new process, introduced in the late 1960s, and it is investigated worldwide as a low cost, energy saving alternative to conventional separation processes such as distillation and reverse osmosis (RO).
Membrane Distillation process allows the separation of volatile components from solutions. If the solutions contains non-volatiles components, it is possible to remove solvent by concentrating the solutions.
The defining phenomenon of MD is relatively simple. A heated, aqueous feed solution is brought into contact with one side (feed side) of a hydrophobic, microporous membrane. The hydrophobic nature of the membrane prevents penetration of the aqueous solution into the pores, resulting in a vapour-liquid interface at each pore entrance.
The driving force for the process is linked to both the partial pressure gradient and the thermal gradient between the two membrane sides. MD can be characterised by the following steps: vaporisation of the more volatile compounds at the liquid/vapour interface and diffusion of the vapour through the membrane pores according to a Knudsen mechanism.
MD is not limited by concentration polarization phenomena as it is the case in pressure driven processes. Therefore, MD allows concentration of aqueous solution by producing fresh water also from highly concentrated feeds where RO cannot operate. Therefore, it is possible to increase the global recovery factor in a seawater desalination system by treating the brine of a RO process with a MD unit. Moreover as hydrodynamics poorly influences permeate fluxes for desalination applications, it is possible to design some membrane modules or systems in which low liquid velocities will be maintained which will allow to reduce the energy costs due to water feeding.

1.2 Types and "versions"

(Describe the most important forms/versions of technology under consideration, including their characteristic features, differences and similarities)

Membrane distillation is a technology in which a microporous hydrophobic membrane is used to promote the mass transfer between phases. A variety of methods may be employed to impose the vapour pressure difference across the membrane to drive flux and, according to the nature of the permeate side of the membrane, MD systems can be classified into four configurations (see Figure 1 below from Ref. 2):
(1) direct contact membrane distillation (DCMD), in which the membrane is in direct contact only with liquid phases, saline water on one side and fresh water on the other, for example; (2) vacuum membrane distillation (VMD), in which the vapour phase is vacuumed from the liquid through the membrane, and condensed, if needed, in a separate device; (3) air gap membrane distillation (AGMD), in which an air gap is interposed between the membrane and the condensation surface; and (4) sweeping gas membrane distillation (SGMD), in which a stripping gas is used as a carrier for the produced vapour, instead of vacuum as in VMD. The type of employed MD depends upon permeate composition, flux, and volatility:

- SGMD and VMD are typically used to remove volatile organic or dissolved gas from an aqueous solution.

- Because AGMD and DCMD do not need an external condenser, they are best suited for applications where water is the permeating flux,
    - the DCMD configuration, which requires the least equipment and is simplest to operate, is best suited for applications such as desalination or the concentration of aqueous solutions (orange juice), in which water is the major permeate component.
    - AGMD, which is the most versatile MD configuration, can be applied to almost any applications.

Regardless of the MD configuration used, water and solute (if the solute is volatile) evaporate from the liquid-vapour interface on the feed side of the membrane, diffuse and/or convect across the membrane, and are either condensed or are removed from the membrane module as vapour on the permeate side.

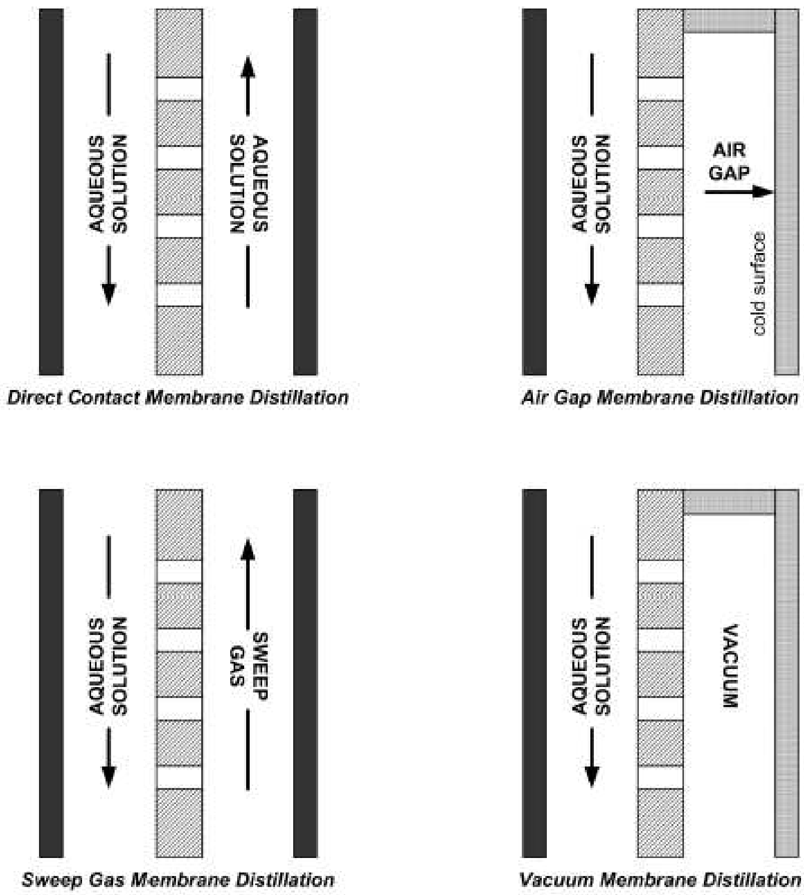

Figure 1: Common configurations of the Membrane Distillation process that may be utilized to establish the required driving force [2].

Osmotic Distillation (OD) represents an extension of the MD concept: a microporous hydrophobic membrane separates two aqueous solutions that are kept in contact at different solute concentrations; this difference in activity causes a vapour-pressure difference that activates mass transport through the membrane. Because OD operates essentially at room temperature, it is appropriate for applications in the agro-food industry (such as in integrated membrane system for the clarification and the concentration of citrus and carrot juices that has been proposed as an alternative and efficient approach to the traditional techniques currently in operation), in pharmaceutical biotechnology and medicine (more information can be found in ref. [35]).

1.3 Potency for Process Intensification: possible benefits

(in Table 1 describe the most important documented and expected benefits offered by the technology under consideration, focusing primarily on energy; CO_2 emission and costs, providing quantitative data, wherever possible. Add other benefits, if needed).

Table 1: Documented and expected benefits resulting from MD application.

Benefit	Magnitude	Remarks
High system compactness and estate saving	The specific area with a fiber of 10^{-3} mm inner diameter can be about 10^4 m^2/m^3, at least 1 order of magnitude higher than those of traditional shell-and tube units in the heat exchanger equipment. In comparison with conventional MSF process, the height of the MSF stage usually is in the range of 4-6 m, high compared with the ≈ 1 cm height of a MD cell. 1 m^2 of MD membrane has a volume of 0.01 m^3 and produce, with current generation configurations, up to 129 kg/m^3h, yielding a volumetric production rate of 12,900 kg/m^3h. The corresponding production rate per m^2 of plant surface area for MSF is 306.7 kg/m^2*h, and considering a 4-m stage height, the MSF process has a volumetric production rate of 76.6 kg/m^3*h, about 40 times lower [30].	The dimensions of the conventional distillation column are orders of magnitude larger than those of a comparable MD plant. In fact, the large vapour space required by a conventional distillation column is replaced in MD by the pore volume of the microporous membrane, which is generally on the order of 100 µm thick. Where conventional distillation relies on high vapour velocities to provide intimate vapour-liquid contact, MD employs a hydrophobic microporous membrane to support a vapour-liquid interface. As a result, MD process equipment can be much smaller, which translates to a saving in terms of real estate [2].
Low operating temperature with respect to the distillation separation processes		The required operating temperature is much lower than that of a conventional distillation column because it is not necessary to heat the process liquids above their boiling temperatures.
Utilization of alternative energy		Because the process can be conducted at temperatures typically below 70°C, and driven by low temperature difference (20°C) of the hot and the cold solutions, low-grade waste and/or alternative energy sources such as solar and geothermal energy can be coupled with MD systems for a cost and energy efficient liquid separation system.
Low operating pressure, lower equipment costs and increased process safety	0 ÷ few hundred kPa	Since MD is a thermally driven process, operating pressure are generally on the order of few hundred kPa, relatively low compared to pressure driven processes such as RO. Lower operating pressure translate to lower equipment costs

		and increased process safety.
High solute rejection	≈ 100%	Since MD operates on the principle of vapour-liquid equilibrium, 100% (theorical) of ions, macromolecules, colloids, cells and other non-volatile constituents are rejected.
Robust membranes		Since the membranes in MD act merely as a support for a vapor-liquid interface, they do not distinguish between solution components on a chemical basis, do not act as a sieve and do not react electrochemically with the solution, they can be fabricated from almost any chemically resistant polymers with hydrophobic intrinsic properties (such as polytetrafluoroethylene (PTFE), polypropylene (PP), and polyvinylidenedifluoride (PVDF)). This characteristic increases membrane life. New amorphous perfluoro polymers (as hyflon, Teflon, etc.) can be also utilized neglecting their still high costs.
Less membrane fouling		Membrane fouling is less of a problem in MD than in other membrane separations because the pores are relatively large compared to the pores in RO and UF; no driving force tends to accumulate on the membrane surface the retentate.
Extremely low sensitivity to concentration polarisation phenomenon		MD permeate flux is only slightly affected by the concentration of the feedwater, and thus, unlike other membrane processes, productivity and performance remain roughly the same for high concentration feed-waters. This means that, by membrane distillation, pure water can also be obtained from highly concentrated feeds, which RO cannot operate.

2. Applications

2.1 Existing technology (currently used)

(Describe technology(-ies) that are conventionally used to perform the same or similar operations as the PI-technology under consideration)

Until now, membrane distillation has been used for applications where water is the permeating flux, such as for the removal of volatile organic or dissolved gas from an aqueous solution, for concentration of juice and wastewater treatment, for the concentration of raw cane sugar and must.
Some of the technologies conventionally used to perform similar operations are: multi-effect distillation (MED), multi-stage flash (MSF), reverse osmosis (RO), electrodialysis/electrodialysis reversal (ED/EDR).

- **Multi-effect distillation (MED)**

The MED process is the oldest technique for seawater desalination.
It is based on heat transport from condensing steam to seawater or brine in a series of stages or effects (Fig. 2). In the first effect, primary steam is condensed for the evaporation of preheated seawater. The secondary steam that is generated in this way is brought to a second effect, operated at slightly lower temperature and pressure; the primary steam condensate is recycled to the steam generator.
The design can be horizontal (HTE) or vertical (VIE).
Problems that may occur with MED are related to corrosion and scaling of oversaturated compounds such as $CaSO_4$. These problems can be very important because of the intense contact between both steam and brine with the heat exchangers.
The performance ratio of water production to steam consumption is generally very high in MED, dependent on the number of effects and approximately equal to the number of effects minus one. The number of effects is limited by a maximal temperature of about 120°C in the first effect (because of the risk of scaling) and a minimal temperature in the last effect that allows heating of the incoming seawater. Additionally, a minimal temperature difference of 5°C is needed in each effect. Therefore, the number of effects is usually between 8 and 16.

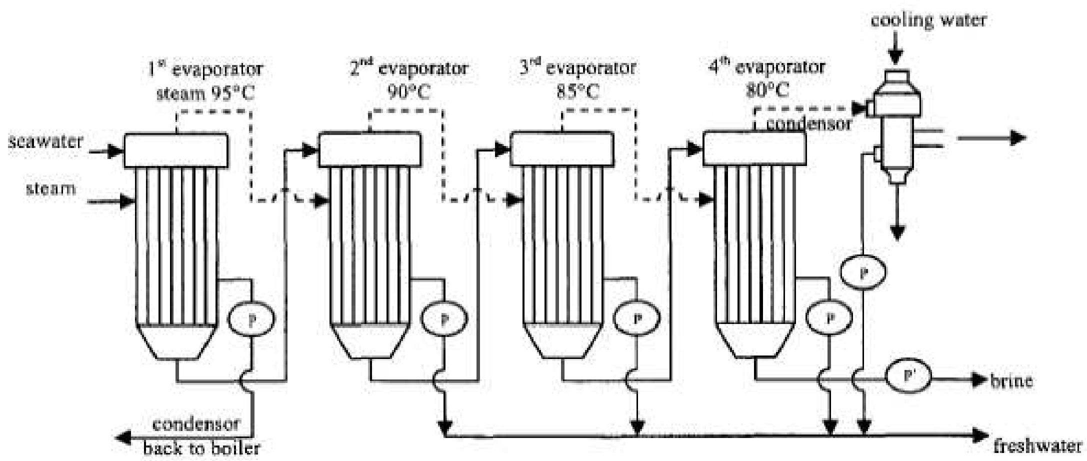

Figure 2: Principle of Multi-Effect Distillation (MED).

- **Multi-stage flash (MSF)**

The principle of operation in MSF is based upon a series of flash chambers where steam is generated from seawater at a progressively reduced pressure (Fig. 3). The steam is condensed by heat exchange with a series of closed pipes where the seawater to be desalted is preheated. The exhausted brine is partly re-circulated to obtain a higher water recovery, and partly rejected to the sea. The main advantage of the MSF process is the ease of the process. Heat exchange with the saline water does not occur through heat transfer surfaces, so that there is no risk of reduced heat transfer by scaling. Precipitation of inorganics may happen within the chambers, and can be reduced by applying acid or antiscalants. The top brine temperature is limited to about 110°C by the risk of scaling. Biocides may be added as well to reduce growth of bacteria; these products will not end up in the product water because of the concept of the process. MSF is also insensitive to the initial feed concentrations and to the presence of suspended particles. The product water contains about 50 ppm of total dissolved salts. Corrosion is easier to control with MSF compared to MED, because the design is less complex. The most important disadvantage of MSF is the lower performance ratio, limited at about 11. This results in a much higher energy consumption, which makes MSF a more expensive technique than MED and only economically competitive when energy costs are very low. However, MSF is still an important process for seawater desalination, although there is a clear tendency towards MED and RO.

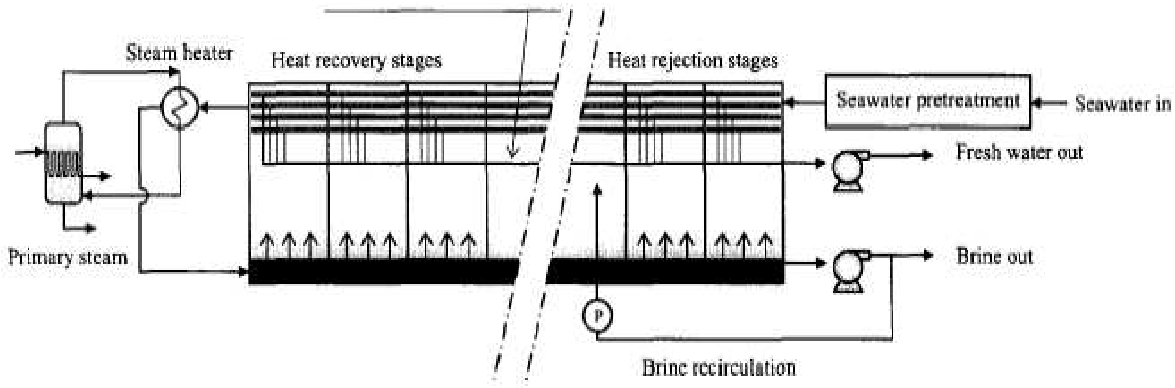

Figure 3: Principle of Multi-Stage Flash (MSF).

- **Reverse osmosis**

Reverse osmosis is a membrane separation process in which the seawater permeates through a membrane by applying a pressure larger than the osmotic pressure of the seawater. The membrane is permeable for water, but not for the dissolved salts. In this way, a separation between a pure water fraction (the permeate) and a concentrated fraction (the retentate or concentrate) is obtained. Pressures needed for the separation are nowadays usually in the range of 50 bar for seawater, 20 bar for brackish water. Most RO membranes are polymeric thin-film composite membranes. The advantages of reverse osmosis are as follows:

a) the low cost of the product water (which can be around 0.50-0.70 US$/m3, compared to 1.0-I .4 US$/m3 for MSF and MED, depending on the energy cost);

b) the permeate quality is very good, with total dissolved solids concentrations between 100 and 500 ppm;

c) high efficiency and operational simplicity;

d) high selectivity and permeability for the transport of specific components and, as a consequence, high rejection values with respect to the different dissolved components (about 90÷99%). Although the rejection values are very high in some cases, such as for boron and arsenic, they are not sufficient to produce water with concentrations that satisfy the WHO drinking water quality guidelines. Therefore, nowadays, the most parts of seawater desalination plants use RO systems with several pass-stages (Figure 4). At the first pass-stage, the most part of salt in the seawater is removed. By treating the resulting product water with other RO membrane elements , usually working at high pH, the solute concentration is brought to below the regulation value.
The disadvantage of RO is the sensitivity of RO membranes to fouling by e.g. suspended solids, and to damage by oxidized compounds such as chlorine or chlorine oxides. Pretreatment is usually needed to ensure a stable performance of the module and optimization of the pretreatment is one of the most critical aspects of RO. Scaling of e.g. $CaCO_3$, $CaSO_3$ and $BaSO_4$ is another possible problem, depending on the recovery ratio of permeate production and feed. At the usual recovery of 50%, scaling can be effectively prevented by adding antiscalants to the water.

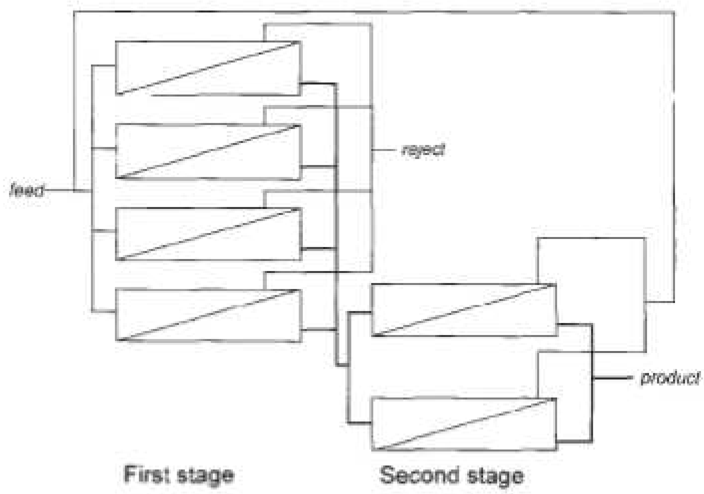

Figure 4: Twin- pass RO system.

- **Electrodialysis / Electrodialysis Reversal**

Electodialysis (ED) has been in commercial use since 1952 for desalting brackish well water in the Arabian Desert, over ten years before reverse osmosis application. An electrodialyzer (Figure 5) consists in a stack of anion- and cation-exchange membrane pairs, with an anode at one end of the stack and a cathode at the other.
When electrodes are connected to an outside source of direct current, like a battery, in a solution of saline water, electrical current is carried through the solution, with the ions tending to migrate to the electrode with the opposite charge. Positively charged ions migrate to the cathode and negatively charged ions migrate to the anode. The anions can move freely through the nearest anion-exchange membrane, but their further progress toward the anode is blocked by the adjacent cation-exchange membrane. In the same manner, the cations move in the opposite direction, through the nearest cation-exchange membrane, but are then blocked from further progress by the adjacent anion-exchange membrane.
By this arrangement, concentrated and diluted solutions are created in the spaces between the alternating membranes; on this basis, it is possible to feed brackish water into the dilution compartment inlet and obtain potable water at its outlet.

Hydrolysis and scaling represent the major obstacles to stable and efficient electrodialyzer operation. The composition of the raw water, and particularly its organic acid content, is also an important determining factor: in fact, organic acids tend to adsorb the anion exchange membrane and thus lead to abnormally high membrane resistance.

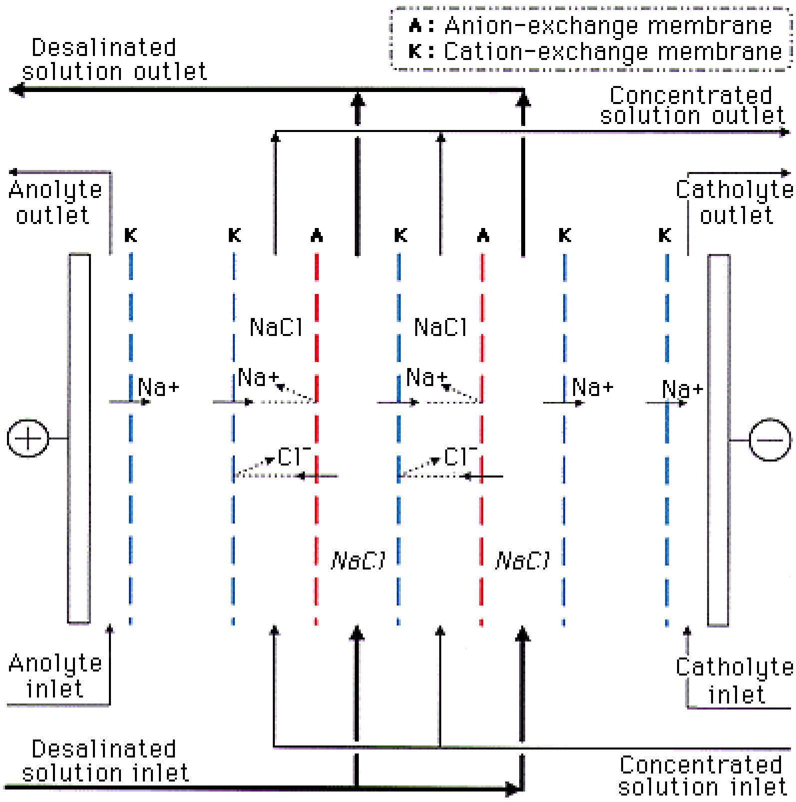

Figure 5: Flow diagram of a typical ED operation.

An Electrodialysis Reversal unit operates on the same general principle as a standard ED plant, except that both product and brine channels are identical in construction. In this process the polarity of the electrodes changes periodically of time, reversing the flow through the membrane. When the polarity is reversed, the desalted stream and brine stream compartments are also reversed. This alternating exposure of membrane surfaces and flow spacers to the product and brine process streams allows operation with brines that have scaling tendencies without dependence on chemical feeds. In particular, EDR plants are much less sensitive to localised scaling, general carbonate scaling due to pH upsets, calcium sulphate scaling and colloidal fouling of membrane surface.
There is a limit on the percentage of ionic salts that can be removed in one pass through an EDR spacer, which is typically 40 to 50%.
To obtain higher salt removals, the water to be desalted flows through stacks in series; each stack is termed a stage. Most EDR plants have two to four stages.

For what concerns energy consumption, electrodialysis is an economically attractive process for low salinity water. In general, the total energy consumption, under ambient temperature conditions and assuming product water of 500 ppm TDS, would be around 1.5 and 4 kWh/m^3 for a feed water of 1,500 to 3,500 ppm TDS, respectively.

2.2 Known commercial applications

(Is the technology broadly applied on commercial scale? In which process industry sectors is the technology most often applied: large volume chemicals – specialty chemicals & pharma – consumer products – ingredients based on agro feedstocks? What is the estimated number of existing application? In Table 2 provide the most prominent examples of realized applications and provide their short characteristics)

Table 2: Industrial-scale applications of the Technology (existing and under realization).

<table>
<tr><th>Sector</th><th>Company-Process/Product name/type</th><th>Short characteristic of application</th><th>Production capacity/ Plant size</th><th>Year of application</th><th>Reported effects</th></tr>
<tr><td>Clean water production</td><td>Memstill process. Plant installed at Senoko Refuse Incineration Plant</td><td rowspan="2">Memstill (a contraction of membrane and distillation) is a distillation technique that uses membranes filtration and waste-heat energy from factories. Waste-heat is a cheap energy source that is plentiful in industrial countries. The cold seawater flows through a condenser with non-permeable walls. Then, the water flows through a heat exchanger where the seawater is heated to 80 degrees Celsius (180 degrees Fahrenheit). The temperature rises a few degrees further with the waste-heat from a nearby factory, which cuts down the energy consumption and CO2 emissions. The cost of desalination of one cubic meter water with Memstill could be under $0.50, where other distillation techniques cost about 1 dollar for the same amount of water. Thanks to the high vapor pressure of the hot seawater, the clean water evaporates through a membrane, while the dirty, salty seawater is left behind. These membranes are made of teflon and are microporous and hydrophobic [39].</td><td>1-2 m^3/hr</td><td>February 2006</td><td rowspan="2">Memstill technology is compact and no uses chemicals. It uses waste heat, therefore there is hardly any production of greenhouses gasses. The salt content in the produced water is reduced by 1,000 times. The energy used is 3 times less than that used in reverse osmosis operation.</td></tr>
<tr><td>Clean water production</td><td>Memstill process. Plant installed at the power plant of E.on on the Maasvlakte</td><td>1-2 m^3/hr</td><td>September 2006</td></tr>
</table>

2.3 Known demonstration project

(Are there any demonstration projects known related to the technology under considerations? In which process industry sectors are those projects carried out: large volume chemicals – specialty chemicals & pharma – consumer products – ingredients based on agro feedstocks? In Table 3 provide the short characteristics of those projects.)

Table 3: Demonstration projects related to the technology (existing and under realization).

Sector	Who is carrying out the project	Short characteristic of application investigated, including product name/type	Aimed year of application	Reported effects
Desalination	**Principal Investigator:** Prof. Takeshi Matsuura, University of Ottawa, Canada **Research Partners:** Prof. M. Khayet, University Complutense of Madrid, Spain MENA Partner, Palestine **Project funded by MEDRC**	**Title of the project: DESIGN OF NOVEL MEMBRANES FOR DESALINATION BY DIRECT CONTACT MEMBRANE DISTILLATION** The objectives of the project are as follows: To prepare hydrophobic/hydrophilic composite membranes with a thin hydrophobic surface layer supported by a relatively thick hydrophilic sub-layer by blending hydrophobic surface modifying macromolecules into hydrophilic host polymers. To carry out DCMD experiments. All DCMD will include the measurement of the salt concentration in permeate and the permeation flux. Comparison of desalination performance by the membranes prepared in this project and the commercially available membranes will be made.	Data not available	Data not available
Desalination	**Principal Investigator:** Prof. Noam Lior University of Pennsylvania, USA **Research Partners:** Mr. Abdulaziz Alklaibi, Saudi Arabia, Ph.D. Student, University of Pennsylvania, USA **Project funded by MEDRC**	**Title of the project: A STUDY OF THE STATE OF THE ART, COMMERCIAL POTENTIAL, AND PROSPECTS FOR ADVANCEMENT OF DESALINATION BY MEMBRANE DISTILLATION** **Objectives** The objective of the project is to explore the potential of membrane distillation for desalination application. The following are the major tasks of the project. To prepare a state of the art review of both the fundamental understanding and practical aspects of membrane distillation. Develop quantitative projections of its commercial feasibility based on the state of the art review. Explore the possible and promising process improvements, which deserve further research. Estimate the commercial consequences if these improvements come to fruition.	**Status** Draft final report is submitted (as of December 2005).	Data not available

Safe water and sanitation	**Principal Investigator:** ROMMEL Matthias (FRAUNHOFER GESELLSCHAFT ZUR FOERDERUNG DER ANGEWANDTEN FORSCHUNG E. V. ,Germany – DE) **Research Partners:** Instituto Tecnologico de Canarias, Spain – ES El Banna for Desalination and Energy Technology, Egypt – EG Fentek - Fenis Teknik Ueruenler AS , Turkey – TR Jordan University of Science and Technology, Jordan – JO Ressources Ingenierie sarl, Morocco - MA	**Title of the project:** PV and thermally driven small-scale, stand alone desalination systems with very low maintenance needs (SMADES) **Objectives** The overall objective of the project is the advancement of stand-alone desalination systems which are based on the highly innovative membrane distillation technology. The objectives are: (l) Evaluation of the present state of the art for small-scale, stand-alone desalination systems with low maintenance needs. (2) To conduct a socio-economic study to determine the specific needs and possibilities for the application of small-scale desalination systems. (3) Development of appropriate small-scale, stand-alone desalination systems with low maintenance needs based on membrane distillation. (4) Development and testing of the membrane distillation components and systems. (5) Dissimination of results in workshops conducted in each of the participating countries. Nature: RS - Research Project Total EC contribution: 600,000 €	Ending date: 31/12/2005	
Water production	**Project leader:** Ir. J.W. Assink **Secretariat:** TNO Quality of Life	**Title of the project:** Memstil membraandestillatietechnologie - Fase II (Membrane distillation: freshwater preparation with a novel distillation technology) **Status:** completed	Period: 11/1998 - 07/2005	
Water production	**Project leader:** Shuguang Deng New Mexico State University, Mexico	**Title of the project:** Integrated Reverse Osmosis and Membrane Distillation for Brackish Water Desalination The project is funded by WERC: A Consortium for Environmental Education and Technology Development at NMSU (New Mexico State University). Deng's project combines reverse osmosis with membrane distillation. The unit will treat one gallon of salt water per minute. The project uses low-grade energy sources and requires significantly less energy than thermal distillation. It utilizes the advantages of reverse osmosis and membrane distillation to produce high-quality fresh water, overcoming the lack of efficiency in reverse osmosis while	Data not available	A scale model is being developed at NMSU and then the project will be applied on a larger scale using water provided by the Tularosa Basin National Desalination Program. With improved technologies, the abundance of saltwater in

		reducing energy and costs. ***Data as of November 2004***		New Mexico could potentially be purified and used as a freshwater supply for residential, agricultural and industrial uses.
Wastewater treatment, Cogeneration, Membrane, Waste heat, Solar energy	**Research leader:** **Andrew Martin, Liu Chuangfeng, Ala'a Kullab** Heat and Power Technology Energy School of Energy and Environmental Technology KTH - Royal Institute of Technology	**Title of the project:** Membrane distillation and applications for water purification The objective of this investigation is to explore the feasibility of membrane distillation (MD) as a complimentary or replacement technology to reverse osmosis and other methods. This technology utilizes heat sources at temperatures well below 100°C, hence it is ideally integrated with waste heat or solar thermal. Research topics include system-wide performance assessments, laboratory investigations, and pilot plant testing in conjunction with Idbäcken Cogeneration Unit (Vattenfall). Applications include water treatment for boilers, district heating networks, and flue gas condensate; ultrapure water production in the semiconductor industry; and solar-assisted desalination	**Period:** 01/01/2004-31/12/2006	
Water production	**Principal Investigator:** Kamalesh Sirkar, New Jersey Institute of Technology	**Title of the project:** Pilot-Scale Studies for Direct Contact Membrane Distillation-Based Desalination Process. Direct Contact Membrane Distillation (DCMD) is a process in which warmer supply water flows over a membrane with cooler water on the other side. A special hollow fiber membrane has been developed for this process. The roles of brine velocity, brine feed temperature, distillate flow rate brine concentrate recirculation rates and others are being determined. Cost estimates of water production will be developed to permit comparison of DCMD with established desalination technologies. Total project cost is $309,811; Reclamation's second year contribution $119,815.	Data not available	Data not available
Water production	**Co-ordinator** Dr Julián Blanco Gálvez, Organization Centro de Investigaciones Medioambientales y Tecnológicas ES-28040 Madrid **Partners:**	**Title of the project:** Seawater desalination by innovative solar-powered membrane-distillation system The main objective of MEDESOL Project is the development of an environmentally friendly improved-cost desalination technology to fresh water supply in arid and semi-arid regions in EU and Third Countries based on solar MD. The layout involves the innovative concept of multistage MD in order	**Duration:** 36 months	Data not available

	Universidad de La Laguna ES; ACCIONA, S.A. ES; AGUAS DE LA CUENCA DEL SUR, S.A. ES; AOSOL- Energias Renováveis, Lda. PT; Universität Stuttgart DE; TINEP S.A. de C.V. MX; Centro de Investigación en Energía-Universidad Nacional Autónoma de México MX; Kungl Tekniska Högskolan SE; Scarab Development AB SE **Project funded during the Sixth Framework Programme of the European Commission**	to minimize specific energy and membrane area required and also to substantially reduce the brine generation. The aim of this work was to evaluate the technical feasibility of producing potable water from seawater by integrating several membrane distillation modules (Multi-step Membrane Distillation System). The aim is to develop systems for a capacity ranging from 0.5 to 50 m3/day. Technical simplicity, long maintenance-free operation periods and high-quality potable water output are the very important aims which will enable successful application of the systems that are based in membrane distillation. The heat source will proceed from an advanced compound parabolic solar concentrator, developed to the specific concentration ratio to achieve the specific needed range of temperatures (90ºC) and the seawater heater will include the development of an advanced non-fouling surface coatings to avoid the deposit formation (i.e. scaling) at such temperature. Laboratory tests under defined testing conditions of all components are very important for the preparation of successful field tests under real conditions. Total Costs: 2.160.144 € Proposed EC grant: 1.385.000 €		
Water production	**Co-ordinator:** Prof. Enrico Drioli, University of Calabria **Partners:** Universität Duisburg – Essen – IWW (Germany); Ben Gurion University (Israel); University of Technology, Sydney (Australia); University of New South Wales (Australia); Carl von Ossietzky University of Oldenburg, Institute for Chemistry and Biology of the Marine Environment (Germany); INSA	**Title:** MEmbrane-based Desalination: an INtegrated Approach RO is today the dominant technology in water desalination. However, some critical issues remain open: improvement of water quality, enhancement of the recovery factor, reduction of the unit water cost, minimizing the brine disposal impact. With the aim to solve these problems, an innovative approach based on the integration of different membrane operations in pre-treatment and post-treatment stages is proposed. Expected outcomes and contributions of the research are: i)the development of advanced analytical methods for feedwater characterization, appropriate fouling indicators and prediction tools, procedures and protocols at full-scale desalination facilities; ii)identification of optimal seawater pre-treatment strategies by designing advanced hybrid membrane processes (submerged hollow fiber filtration/reaction, adsorption/ion exchange/ozonation) and comparison with conventional methods; iii)the optimization of RO membrane module configuration, cleaning strategies, reduction of scaling potential by	**Duration:** 36 months	

	Toulouse (France); UNESCO – IHE (The Netherlands); Centre National de Recherche Scientifique (France); Ecole Nationale d'Ingénieurs GABES (Tunisia); KIWA (The Netherlands); Anjou Recherche – Veolia Water (France); GVS S.P.A. (Italy) **Project funded during the Sixth Framework Programme of the European Commission**	NF; iv)the development of strategies aiming to approach the concept of Zero Liquid Discharge (increasing the water recovery factor up to 95% by using Membrane Distillation - MD;bringing concentrates to solids by Membrane Crystallization or Wind Intensified Enhanced Evaporation) and to reduce the brine disposal environmental impact and cost; v)increase the sustainability of desalination process by reducing energy consumption(evaluation of MD, demonstration of a new energy recovery device for SWRO installations)and use of renewable energy (wind and solar). The research team embodies science and engineering from both the practitioner and academic perspectives. Potential end-users and participating utilities will be involved in research activities and applications. Linkages with ongoing research activities and demonstration studies at full-scale desalination plants will be conducted to ensure the applicability and transfer of the findings of the proposed research project. Total Costs: 6.349.500 € Proposed EC grant: 3.300.000 €		
Food	**Research convention funded by ITEST S.r.l (Corato, Bari – ITALY)**	**Title of the convention: New plant for the concentration of grape juice through integrated osmotic technologies** The aim of the convention was the adjustment of a prototype of an integrated plant with ultrafiltration, reverse osmosis and osmotic distillation operations, for the production of concentrated grape juice.	**Duration:** 12 months (July 2006 – July 2007)	Data not available
Food	**Project Coordinator: PARMALAT SpA (Parma, ITALY)** **Partners:** Istituto Mario Negri Sud; San Giorgio Flavors S.r.l.; Emmegi Agroindustriale; Stazione Sperimentale Industria Conserve Alimentari; Tecnoalimenti S.C.p.A.; Università di Parma; ITM-CNR. **Funding Board: MIUR**	**Title of the project: New products from fruit and vegetables with high nutritional value (PNR- Tema 2)** Aim of the project was the development of new technologies for the production of concentrated liquid foods from fruit and vegetable as alternative to the traditional processes of the agro-food industry. An integrated membrane process, founded on ultrafiltration, reverse osmosis and osmotic distillation was developed both for the clarification and concentration of carrot and citrus fruit juices, and for the production of juices with high nutritional value and high organoleptic quality.	**Duration:** 36 months (1999-2001)	Data not available
Water	**Project**	**Title of the project: INNOWA**	Ended (May	Data not

	Coordinator: University of Applied Sciences Karlsruhe (UASK) – GERMANY **Partners:** Institute for Membrane Technology (ITM-CNR) c/o University of Calabria (ITALY); Shah Jalal University of Science & Technology (SUST) Sylhet (BANGLADESH); Jiangsu Polytechnic University (JPU) Changzhou (PR CHINA) **Project funded by Asia ProEco Call**	A project funded by European Commission in the Asia Pro Eco Programme which aims at building capacity for technology transfer by establishing an European-Asian technology network on innovative water treatment technologies with focus on membrane techniques. The overall objective of the project is to contribute significantly to reduction of waterborne diseases and illnesses in the Asian target countries, particularly among poor families. This means to contribute to better health conditions by improved drinking water quality and reduced toxic industrial waste water discharge into the rivers.	2005-May 2007)	available
Food	**Research project funded by PARMALAT (Collecchio – IT)** **Partners:** Institute for Membrane Technology (ITM-CNR) c/o University of Calabria (ITALY)	**Title of the project: Applicazione dei membrane contactors in sistemi integrati per ottenere acque a composizione controllata**	Ended	Ended
Food	**Research project funded by PARMALAT (Collecchio – IT)** **Partners:** Institute for Membrane Technology (ITM-CNR) c/o University of Calabria (ITALY)	**Title of the project: Integrated membrane operation for special water preparation**	Ended	Ended

2.4 Potential applications discussed in literature

(Provide a short review, including, wherever possible, the types/examples of products that can be manufactured with this technology.)

As reported in section 1.2, the type of employed MD depends upon several parameters such as permeate composition, flux, and volatility. Table 4 broadly summarizes areas where the different MD configurations were examined, on laboratory scale, and found to be applicable. Table 5 shows some MD applications reported in literature.

MD has been applied for separation of non-volatile components from water like ions, colloids, macromolecules [2-9], for the removal of trace volatile organic compounds from water such as benzene, chloroform, trichloroethylene [2, 10-15] or the extraction of other organic compounds such as alcohols from dilute aqueous solutions [2, 16-19]. As a consequence, MD is suited for both concentration of aqueous solutions and water production. In fact, MD has been applied for water desalination (where near 100% rejection of non-volatile ionic solutes is easily achieved), wastewater treatment and food processing (concentration of juice and raw cane sugar), biomedical applications (such as water removal from blood and treatment of protein solutions) [1]. Separation of azeotropic aqueous mixtures such as alcohol–water mixtures, concentration of radioactive solutions and application for nuclear desalination, waste water treatment in which a less hazardous waste can be discharged to the environment specially in textile waste treatment that is contaminated with dyes, concentration of coolant (glycol) aqueous solutions, treatment of humic acid solutions, pharmaceutical waste water treatment and in areas where high temperature applications lead to degradation of process fluids, can be attractive [11].

In addition, due to the chemical stability of the employed membranes, MD can also be applied for the concentration of acids [20-22]. In fact, the concentration of sulfuric acid, hydrochloric acid and nitric acid by both DCMD and VMD up to 60% has been achieved.

Table 4: Membrane Distillation applications

Application	**Configuration**
Desalination and pure water production from brackish water	DCMD, AGMD, SGMD, VMD
Nuclear industry (concentration of radioactive solutions and wastewater treatments; pure water production)	DCMD
Textile industry (removal of dyes and wastewater treatment)	DCMD, VMD
Chemical industry (concentration of acids, removal of VOCs from water, separation of azeotropic aqueous mixtures such as alcohol/water mixtures and crystallization)	DCMD, AGMD, SGMD, VMD
Pharmaceutical and biomedical industries (removal of water from blood and protein solutions, wastewater treatment)	DCMD
Food industry (concentration of juices and milk processing) and in areas where high temperature applications lead to degradation of process fluids	DCMD, AGMD, VMD

Table 5: Membrane Distillation applications reported in literature.

Reference	Application	Configuration
Calabrò et al. [23]	Wastewater treatment	DCMD
Nene et al.[24]	Concentration of raw cane sugar	DCMD
Calabrò et al. [25]	Concentration of orange juice	DCMD
Bandini et al. [26]	Concentration of must	VMD
Laganà et al. [27]	Concentration of apple jiuce	DCMD
V.D. Alves, I.M. Coelhoso [28]	Concentration of a sucrose solution, used as a model fruit juice	DCMD
Corinne Cabassud, David Wirth [29]	Seawater desalination	VMD

3. What are the development and application issues?

3.1 Technology development issues

(In Table 6 list and characterize the essential development issues, both technical and non-technical, of the technology under consideration. Pay also attention to "boundary" issues, such as instrumentation and control equipment, models, etc.). Also, provide your opinion on how and by whom these issues should be addressed)

Table 6: Technology development issues.

Issue	Description	How and by whom should issue be addressed?
Development of proper membranes for MD application	The used membranes in most of the MD studies are usually manufactured for other processes (i.e. microfiltration) rather than MD. The need for new membranes, manufactured especially for MD purposes, have been widely accepted by MD investigators, also if the required features to MD membranes are met with the commercially available membranes. The new membranes should have to increase transmembrane vapour pressure difference through minimizing the heat loss by conduction through the membrane.	A more intensive and focused research effort both in experimentation and modelling, and the construction of pilot plants for scale-up studies are necessary.
Development of proper modules for MD application	Advancements in module design for improving transmembrane fluxes, through minimizing boundary layer heat and mass transfer resistances. Advancements in module design for minimizing the heat losses through the membrane and to the environment. While the temperature polarization effect can be diminished by working under turbulent flow regime and with the aid of turbulence promoters (i.e. good module design), the heat loss by conduction through the membrane can be minimized by increasing pores size and porosity. Proper isolation of membrane module, its piping and other accessories can reduce heat loss to environment.	
Finding new MD applications	MD technique can be successful applicable in areas where high temperature can not be applied because produces degradation and denaturalization of the components present in the feed solutions.	

3.2 Challenges in developing processes based on the technology

(In Table 7 list and characterize the essential challenges, both technical and non-technical, in developing commercial processes based on the technology under consideration. Also, provide your opinion on how and by whom these challenges should be addressed)

Table 7: Challenges in developing processes based on the technology

Challenge	Description	How and by whom should the challenge be addressed?
Reduction of high cost of commercial MD modules.	Most researchers use modules designed for other membrane operations. As a consequence, there is a lack of commercially available MD units.	A more intensive and focused research effort both in experimentation and modelling, and the construction of pilot plants for scale-up studies are necessary.
Production and investigation of larger MD membrane modules	As most of the investigators use modules designed for other operations, for potential commercial applications of MD technology, much larger membrane modules having the required effective surface area should be investigated.	
Integration of MD technique with other operations	Integration of MD with other processes, such as reverse osmosis (RO), ultrafiltration (UF), nanofiltration (NF),can extend the separation efficiency of the whole integrated system.	
Development of energy integration technique.	The possibility to utilize capability to utilize low-grade waste and/or alternative energy sources, such as solar and geothermal energy, makes MD a promising separation technique. A possible and promising application is drinking water production in dry rural areas using solar energy; another possible area for MD implementation is the nuclear industry or nuclear power stations, which are rich sources in waste heat.	

4. Where can information be found?

4.1 Key publications

(Provide the list of key publications in Table 8)

Table 8: Key publications on the technology.

Publication	Publication type (research paper/review/book/report)
[1] M.S. El-Bourawi, Z. Ding, R. Ma, M. Khayet, *A framework for better understanding membrane distillation separation process*, Journal of Membrane Science 285 (2006) 4–29.	Research paper
[2] K.W. Lawson, D.R. Lloyd, *Membrane distillation*, J. Membr. Sci. 124 (1997) 1–25.	Review
[3] J.I. Mengual, L. Pena, *Membrane distillation*, Colloid Interf. Sci. 1 (1997) 17–29.	Research paper
[4] K.W. Lawson, D.R. Lloyd, *Membrane distillation. I. Module design and performance evaluation using vacuum membrane distillation*, J. Membr. Sci. 120 (1996) 111–121.	Research paper
[5] M. Khayet, M.P. Godino, J.I. Mengual, *Theoretical and experimental studies on desalination using the sweeping gas membrane distillation*, Desalination 157 (2003) 297–305.	Research paper
[6] M. Khayet, J.I. Mengual, G. Zakrzewska-Trznadel, *Direct contact membrane distillation for nuclear desalination. Part II. Experiments with radioactive solutions*, Int. J. Nucl. Desalinat. (IJND) 56 (2006) 56–73.	Research paper
[7] M. Sudoh, K. Takuwa, H. Iizuka, K. Nagamatsuya, *Effects of thermal and concentration boundary layers on vapor permeation in membrane distillation of aqueous lithium bromide solution*, J. Membr. Sci. 131 (1997) 1–7.	Research paper
[8] E. Drioli, V. Calabrò, Y.Wu, *Microporous membranes in membrane distillation*, Pure Appl. Chem. 58 (12) (1986) 1657–1662.	Research paper
[9] P.P. Zolotarev, V.V. Ugrosov, I.B. Volkina, V.N. Nikulin, *Treatment of waste-water for removing heavy-metals by membrane distillation*, J. Hazard. Mater. 37 (1) (1994) 77–82.	Research paper
[10] S.H. Duan, A. Ito, A. Ohkawa, *Removal of trichloroethylene from water by aeration, pervaporation and membrane distillation*, J. Chem. Eng. Jpn. 34 (8) (2001) 1069–1073.	Research paper
[11] F.A. Banat, J. Simandl, *Removal of benzene traces from contaminated water by vacuum membrane distillation*, Chem. Eng. Sci. 51 (8) (1996) 1257–1265.	Research paper
[12] G.C. Sarti, C. Gostoli, S. Bandini, *Extraction of organic-compounds from aqueous streams by vacuum membrane distillation*, J. Membr. Sci. 80 (1993) 21–	Research paper

33.	
[13] N. Qureshi, M.M. Meagher, R.W. Hutkins, *Recovery of 2,3-butanediol by vacuum membrane distillation*, Sep. Sci. Technol. 29 (13) (1994) 1733–1748.	Research paper
[14] F.A. Banat, M. Al-Shannag, *Recovery of dilute acetone–butanol–ethanol (ABE) solvents from aqueous solutions via membrane distillation*, Bioprocess Eng. 23 (6) (2000) 643–649.	Research paper
[15] F.A. Banat, J. Simandl, *Membrane distillation for propane removal from aqueous streams*, J. Chem. Technol. Biotechnol. 75 (2) (2000) 168–178, AGMD.	Research paper
[16] M.C. Garcia-Payo, M.A. Izquierdo-Gil, C. Fernandez-Pineda, *Air gap membrane distillation of aqueous alcohol solutions*, J. Membr. Sci. 169 (2000) 61–80.	Research paper
[17] F.A. Banat, J. Simandl, *Membrane distillation for dilute ethanol separation from aqueous streams*, J. Membr. Sci. 163 (1999) 333–348.	Research paper
[18] S. Bandini, A. Saavedra, G.C. Sarti, *Vacuum membrane distillation: experiments and modeling*, AIChE J. 43 (2) (1997) 398–408.	Research paper
[19] S. Bandini, G.C. Sarti, *Heat and mass transfer resistances in vacuum membrane distillation per drop*, AIChE J. 45 (7) (1999) 1422–1433.	Research paper
[20] M. Tomaszewska, *Concentration of the extraction of fluid from sulphuric acid treatment of phosphogypsum by membrane distillation*, J. Membr. Sci. 78 (1993) 277–282.	Research paper
[21] M. Tomaszewska, M. Gryta, A.W. Morawski, *Study on the concentration of acids by membrane distillation*, J. Membr. Sci. 102 (1995) 113–122.	Research paper
[22] J.J. Tang, K.G. Zhou, F.G. Zhao, R.X. Li, Q.X. Zhang, *Hydrochloric acid recovery from rare earth chloride solutions by vacuum membrane distillation (1) Study on the possibility*, J. Rare Earths 21 (2003) 78–82.	Research paper
[23] V. Calabrò, E. Drioli and F. Matera, *Membrane distillation in the textile wastewater treatment*, Desalination, 83 (1991) 209-224.	Research paper
[24] S. Nene, S. Kaur, K. Sumod, B. Joshi and K.S.M.S. Raghavarao, *Membrane distillation for the concentration of raw cane-sugar syrup and membrane clarified sugarcane juice*, Desalination, 147 (2002) 157-160.	Research paper
[25] V. Calabro, B.L. Jiao and E. Drioli, *Theoretical and experimental study on membrane distillation in the concentration of orange juice*, Ind. Eng. Chem. Res., 33 (1994) 1803-1808.	Research paper
[26] S, Bandini and G.C. Sarti, *Concentration of must through vacuum membrane distillation*, Desalination, 149 (2002) 253-259.	Research paper
[27] F. Lagana, G. Barbieri, E. Drioli, *Direct contact membrane distillation: modeling and concentration experiments*, J. Membr. Sci., 166 (2000) 1-11.	Research paper
[28] V.D. Alves, I.M. Coelhoso, *Orange juice concentration by osmotic evaporation and membrane distillation: A comparative study*, Journal of Food Engineering 74 (2006) 125–133.	Research paper
[29] Corinne Cabassud, David Wirth, *Membrane distillation for water desalination: how to chose an appropriate membrane?*, Desalination 157 (2003) 307-314.	Research paper
[30] A. M. Alklaibi, Noam Lior, *Membrane-distillation desalination: status and potential*, Desalination 171 (2004) 111-131.	Research paper
[31] E. Curcio, E. Drioli, *Membrane Distillation and Related Operations-A Review*, Separation and Purification Reviews, 34 (2005) 35-85.	Review
[32] E. Drioli, F. Laganà, A. Criscuoli, G. Barbieri, *Integrated membrane operations in desalination processes*, Desalination, 122 (1999) 141-145.	Research paper
[33] K. Schneider, W. Holz, R. Wollbeck, *Membranes and modules for transmembrane distillation*, J. Mem. Sci., 39 (1988) 25-42.	Research paper
[34] J. Phattaranawik, R. Jiraratananon, A.G. Fane, *Heat transport and membrane distillation coefficients in direct contact membrane distillation*, Journal of Membrane Science 212 (2003) 177–193	Research paper
[35] E. Drioli, A. Criscuoli, E. Curcio, *Membrane Contactors: Fundamentals, Applications and Potentialities*, Membrane science and technology series, 11, Amsterdam; Boston: Elsevier, 2006	Book
[36] E. Drioli, E. Curcio, G. Di Profio, F. Macedonio, A. Criscuoli, *Integrating Membrane Contactors Technology and Pressure-Driven Membrane Operations for Seawater Desalination: Energy, Exergy and Cost Analysis*, Chemical	Research paper

Engineering Research and Design, 84 (A3) (2006) 209–220.	
[37] F. Macedonio, E. Curcio, E. Drioli, *Integrated Membrane Systems for Seawater Desalination: Energetic and Exergetic Analysis, Economic Evaluation, Experimental Study*, Desalination, 203 (2007) 260–276.	Research paper
[38] Khayet, M., Mengual, J.I., Zakrzewska-Trznadel, G., *Direct contact membrane distillation for nuclear desalination. Part I: Review of membranes used in membrane distillation and methods for their characterisation*, Int. J. NuclearDesalination, Vol. 1, No. 4, (2005) pp.435–449.	Review
[39] http://www.freshtechnology.net/science-memstill.php	Web page
[40] E. Drioli, Y. Wu, V. Calabrò, *Membrane distillation in the treatment of aqueous solutions*, J. Membrane Sci., 33, 277, 1987.	Research paper
[41] E. Drioli, Y. Wu, *Membrane distillation: an experimental study*, Desalination, 53, 339, 1985.	Research paper
[42] B. L. Jiao, R. Molinari, V. Calabrò, E. Drioli, *Application of membrane operations in concentrated citrus juice processing*, Agro-Industry Hi-Tech, 18-27, 1994.	Research paper
[43] Y. Wu, Y. Kong, J. Liu, J. Zhang, J. Xu, *An experimental study on membrane distillation - crystallization for treating waste water in taurine production*, Desalination, 80, 235, 1991.	Research paper

4.2 Relevant patents and patent holders

(Provide the list of relevant patents in Table 9. Under "remarks" provide, where applicable, the names/types of products targeted by the given patent.)

Table 9: Relevant patents

Patent	Patent holder	Remarks, including names/types of products targeted by the patent
SILICONE RUBBER VAPOUR DIFFUSION IN SALINE WATER DISTILLATION **United StatesPatent Serial No.** *285,032*.	Bodell, B.R. (1963)	First patent on MD
RECOVERY OF DEMINERALIZED WATER FROM SALINE WATERS **United States Patent** 3, 340, 186 (1967).	P. K. Weyl	Membrane distillation methods
U.S. Pat. No. 4,545,862	Gore et al.	Membrane distillation methods
U.S. Pat. Nos. 4,265,713, 4,476,024, 4,419,187 and 4,473,473	all by Cheng et al.	Method and apparatus for distillation
(WO/2006/137808) CONTAMINATED INFLOW TREATMENT WITH MEMBRANE DISTILLATION BIOREACTOR	**Applicants:** NANYANG TECHNOLOGICAL UNIVERSITY [SG/SG]; 50 Nanyang Avenue, Singapore 639798 (SG) *(All Except US)*. FANE, Anthony, G. [AU/AU]; 129 Peninsular Rd., Grays Point, NSW 2232 (AU) *(US Only)*. PHATTARANAWIK, Jirachote [TH/SG]; Bragevegen 7, N-7032 Trondheim (NO) *(US Only)*. WONG, Fook-Sin [AU/SG]; Block 1B, Pine Grove #07-05, Singapore 591001 (SG) *(US Only)*. **Inventors:**	The present invention relates to inflow treatment, and in particular to treatment of contaminated inflow using bioreactors and distillation membranes.

	FANE, Anthony, G. [AU/AU]; 129 Peninsular Rd., Grays Point, NSW 2232 (AU). PHATTARANAWIK, Jirachote [TH/SG]; Bragevegen 7, N-7032 Trondheim (NO). WONG, Fook-Sin [AU/SG]; Block 1B, Pine Grove #07-05, Singapore 591001 (SG).	
(WO/2003/000389) MEMBRANE-ASSISTED FLUID SEPARATION APPARATUS AND METHOD	**Applicants:** PETRO SEP INTERNATIONAL LTD. [CA/CA]; 2270 Speers Road Oakville, Ontario L6L 2X8 (CA) (All Except US). BAIG, Fakhir, U. [CA/CA]; 2200 Grenville Drive Oakville, Ontario L6H 6W9 (CA) (US Only). KAZI, Abdul, M. [CA/CA]; 1244 Blackburn Drive Oakville, Ontario L6M 2N5 (CA) (US Only). AL-HASSANI, Aiser [CA/CA]; 2781 Lindholm Crescent Mississauga, Ontario L5M 2N5 (CA) (US Only). **Inventors:** BAIG, Fakhir, U. [CA/CA]; 2200 Grenville Drive Oakville, Ontario L6H 6W9 (CA). KAZI, Abdul, M. [CA/CA]; 1244 Blackburn Drive Oakville, Ontario L6M 2N5 (CA). AL-HASSANI, Aiser [CA/CA]; 2781 Lindholm Crescent Mississauga, Ontario L5M 2N5 (CA).	This invention relates to fluid separation. In particular, this invention relates to a fluid separation apparatus comprising of hollow fiber membranes used in fluid processing and a method of fluid separation, including a method of internal heat recovery therein.
WATER PURIFIER HAVING DEGASSOR AND MEMBRANE DISTILLATION ELEMENTS **United States Patent** 5788835 **US Patent Issued** on August 4, 1998	**Assignee:** H.V. Water Purification AB **Application:** No. 492098 filed on 1995-06-29	The present invention relates to a water purifier of the kind defined in the preamble of claim 1, and then particularly to a water purifier for domestic use. More specifically, the invention relates to a water purifier which purifies water by membrane distillation.
METHODS AND DEVICE FOR THE PURIFICATION, ESPECIALLY DESALINATION, OF WATER	**Patent Agent:** Rothwell, Figg, Ernst & Manbeck, P.C. - Washington, DC, US **Patent Inventors:** Guenther Hambitzer, Heide Biollaz, Markus Borck, Christiane Ripp **Applicaton #:** 20060108286 **Class:** 210637000 (USPTO)	
APPARATUS FOR DESALTING SALT BY MEMBRANE DISTILLATION **European classification:** B01D13/00F **Publication number:** FI870919 **Publication date:** 1987-03-03 No.44503 **Application number:** FI19870000919 19870303	**Inventor:** KJELLANDER NILS (SE); RODESJOE BO (SE) **Applicant:** SVENSKA UTVECKLINGS AB (SE)	Apparatus for desalinating sea water, comprising a distillation unit and a condensation surface arranged at a distance from the membrane.
SYSTEM FOR TREATING WASTE ORGANIC SOLVENT AND THIN MEMBRANE	**Inventors (Country):** KUSAKABE, FUMIYUKI (Japan) FUJII, TADAO (Japan)	The invention provides an automated system for continuously recovering

DISTILLATION APPARATUS INCORPORATED THEREIN **Patent Application:** CA 2046971 **Application No.:** 3-49064 **Country:** Japan **Date:** Feb. 21, 1991	MORISHITA, FUMIO (Japan) OHTA, SHIRO (Japan) **Owners (Country):** KUSAKABE, FUMIYUKI (Not Available) FUJII, TADAO (Not Available) MORISHITA, FUMIO (Not Available) OHTA, SHIRO (Not Available) TOYOTA KAGAKU KOGYO KABUSHIKI KAISHA (Japan) TOYOTA KAGAKU KOGYO KABUSHIKI KAISHA (Not Available)	renewable volatile compounds by boiling points from waste organic solvent with minimum energy loss, and an improved thin membrane distillation apparatus for efficient distillation of renewable volatile compounds from waste organic solvent and enforced discharge of the residue or sludge.

4.3 Institute/companies working on the technology

(Provide the list of most important research centres and companies in Table 10)

Table 10: Institutes and companies working on the technology

Institute/Company	Country	Remarks
Fraunhofer Institute for Solar Energy Systems ISE Freiburg.	Germany	-
Institute on Membrane Technology ITM-CNR c/o University of Calabria.	Italy	-
Department of Chemical Engineering and Material, University of Calabria	Italy	-
Insa Toulouse.	France	-
Environmental Application of Solar Energy and Characterisation of Solar Radiation, Plataforma Solar de Almería.	Spain	-
SINTEF Materials Technology	Norway	-
Center For Membrane Technologies, Otto H. York Department of Chemical Engineering, New Jersey Institute of Technology.	USA	-
College of Life Science and Technology, Beijing University of Chemical Technology, Beijing.	China	-
TNO	Netherlands	-
Institute of Chemical and Environment Engineering, Szczecin University of Technology.	Poland	-
Department of Applied Physics 1, Faculty of Physics, University Complutense of Madrid,	Spain	-

5. Stakeholders

5.1 Suppliers and developers

(Provide the list of key suppliers/developers in Table 11)

Table 11: Suppliers and developers.

Membrane Trade Name/ *Manufacturer*	Material	Structural Characteristic	Application	Bibliography Reference	Contact
S6/2 MD020CP2N/ *AkzoNobel Microdyn*	PP (polypropylene capillary membrane: number of capillaries in membrane module=40; effective filtration area=0.1m2; inner capillary diameter=1.8 mm; length of capillaries= 470mm)	Thickness = 450 µm; average pore size = 0.2 µm; porosity = 70%.	Microdyn – Nadir Produces polymeric membrane (in polyamide, polypropylene) and polypropylene hydrophobic membrane. Applications include water and wastewater treatment, food and pharmaceutical industry.	M. Khayet, J.I. Mengual, T. Matsuura, Porous hydrophobic/hydrophilic composite membranes Application in desalination using direct contact membrane distillation, Journal of Membrane Science 252 (2005) 101–113	**Microdyn – Nadir** Microdyn Modulban Gmbh Öhder Straße 28 – 42289 Wuppertal, Germany Postfach 240252 . 42232 Wuppertal Tel.: +49 (0) 202 26092 – 0 Fax: +49 (0) 202 26092 – 25 e-mail: sales@microdyn-nadir.de Web site: www.microdyn-nadir.de
Liqui-Cel®			Liqui-Cel® Membrane Contactors are used for degassing liquids. They are widely used for O_2 removal from water as well as CO_2 removal from water. They have displaced the vacuum tower, forced draft de-aerator, and oxygen scavengers.		http://www.liqui-cel.com/ 13800 South Lakes Drive Charlotte, North Carolina 28273, USA Tel.: 704 588 5310 Fax: 704 587 8585

			Liqui-Cel®, SuperPhobic® and MiniModule® Membrane Contactors are used extensively for de-aeration of liquids in the microelectronics, pharmaceutical, power, food & beverage, industrial, photographic, ink and analytical markets.		
TNO					info-beno@tno.nl drs. A.E. (Albert) Jansen Business Developer Separation Technology Phone: +31 55 549 39 43
Scarab Development AB			Invests in Development of Technology for Water Purification, Solar Power, Poly-Generation, Recycling and Sustainable Systems		Street: Nybrogatan 12. 2 tr City: 114 39 Stockholm Country: Sweden Telephone: (+46) 8 - 660 39 70 Fax: (+46) 8 - 662 96 18
Membranes from *GVS S.p.A.*	PVDF flat hydrophobic membranes				sng@gvs.com
Membranes from PP (*Membrana GmbH*, Germany) with microfiltration properties.			Commercial hollow fiber membranes from PP (Membrana GmbH, Germany) with microfiltration properties are often applied in gas/liquid contactors. Membrana GMBH produces polyethylene, polypropylene, polyetersulfon, cellulose and polymeric membranes.	W. Albrecht, R. Hilke, K. Kneifel, Th. Weigel, K.-V. Peinemann, Selection of microporous hydrophobic membranes for use in gas/liquid contactors: An experimental approach, Journal of Membrane Science 263 (2005) 66–76	**Membrana GMBH** Öhder Straße 28, D – 42289 Wuppertal, Germany Postfach 200151, D – 42201 Wuppertal Tel.: (0) 202 6099-651 Fax: (0) 202 6099 602 e-mail: info@membrana.de Web site: http://www.membrana.com
Accurel_ PP Q3/2	Accurel_ PP Q3/2.	Nominal pore diameter of 0.2 lm,	Accurel_ PP Q3/2: utilized for	V.D. Alves, I.M. Coelhoso, Orange	

(*Membrana GmbH, Germany*). Accurel_ PP 2E HF (*Membrana GmbH, Germany*).	Accurel_ PP 2E HF:	70% porosity, an internal diameter of 600 μm, a thickness of 200 μm and 20 cm long. Active area of 34 cm^2, a nominal pore diameter of 0.2 μm, a thickness of 165 μm and 60–75% porosity	the concentration of the sucrose solution and of the orange juice (using hollow fiber membrane contactor with an internal area of 0.16 m^2, containing 400 polypropylene fibres) Accurel_ PP 2E HF: utilized for the transport of the aroma compounds using a stainless steel cell with the polypropylene membrane Accurel_ PP 2E HF.	juice concentration by osmotic evaporation and membrane distillation: A comparative study, Journal of Food Engineering 74 (2006) 125–133 A. Bottino, G. Capannelli, A. Comite, Novel porous poly (vinylidene fluoride) membranes for membrane distillation, Desalination 183 (2005) 375–382	
Pall-Microza PVDF fibres			Hollow-fibre modules containing Pall-Microza PVDF fibres used for VMD for water desalination.	Corinne Cabassud, David Wirth, Membrane distillation for water desalination: how to chose an appropriate membrane?, Desalination 157 (2003) 307-314	http://www.pall.com/microe.asp
TF200 TF450 TF1000 from *Pall–Gelman*	They are made of a thin polytetrafluoroethylene (PTFE) macroporous layer supported by a polypropylene (PP) net.	Thickness = 178 μm; average pore size = 0.2, 0.45 and 1.00 μm, respectively; porosity = 80%.		Mathilde Courel, Manuel Dornier*;* Gilbert Marcel Rios, Max Reynes, Modelling of water transport in osmotic distillation using asymmetric membrane, Journal of Membrane Science 173 (2000) 107–122 M. Courel, E. Tronel-Peyroz, G.M. Rios, M. Dornier, M. Reynes, The problem of membrane characterization for the process of osmotic distillation, Desalination 140 (2001) 15-25 L. Martinez-Diez,	sales@VGDLLC.com

				F.J. Florido-Diaz, Desalination of brines by membrane distillation, Desalination 137 (2001) 267-273 M. Khayet, J.I. Mengual, T. Matsuura, Porous hydrophobic/hydrophilic composite membranes Application in desalination using direct contact membrane distillation, Journal of Membrane Science 252 (2005) 101–113	
Commercial *Gelman* polyvynilidene fluoride (PVDF) membranes			Commercial porous hydrophobic membranes for MD.	J.M. Ortiz de Zfirate, L. Pefia, J.I. Mengual, Characterization of membrane distillation membranes prepared by phase inversion, Desalination 100 (1995) 139-148	
Millipore polytetra-fluoroethilene (PTFE) membranes and polyvynilidene fluoride (PVDF) membranes			Commercial porous hydrophobic membranes for MD	J.M. Ortiz de Zfirate, L. Pefia, J.I. Mengual, Characterization of membrane distillation membranes prepared by phase inversion, Desalination 100 (1995) 139-148	
Durapore GVSP (PVDF)/ *Millipore* UPVP (UHMWPE)/ *Millipore*	GVSP: Surface modified polyvinylidene fluoride (PVDF), UPVP: Ultra high MW polyethylene (UHMWPE),	Nominal pore diameter = 0.2 μm, porosity 80%, thickness 108 μm. Nominal pore diameter = 0.2 μm, porosity 80%, thickness 90 μm.	These membranes are porous, hydrophobic and flat sheet. Commercial porous hydrophobic membranes for MD.	J.M. Ortiz de Zfirate, L. Pefia, J.I. Mengual, Characterization of membrane distillation membranes prepared by phase inversion, Desalination 100 (1995) 139-148 J. Mansouri, A.G. Fane, Osmotic distillation of oily feeds, Journal of Membrane Science 153 (1999) 103±120	

GVHP HVHP /*Millipore*	PVDF (flat-sheet polyvinylidene fluoride membranes)	Thickness = 110 and 140 µm, respectively; average pore size = 0.22 and 0.45 µm, respectively; porosity = 75%.		M. Khayet, J.I. Mengual, T. Matsuura, Porous hydrophobic/hydrophilic composite membranes Application in desalination using direct contact membrane distillation, Journal of Membrane Science 252 (2005) 101–113	
Celgard 2500 (PP/PE, *Hoechst Celanese*).	Celgar 2500: Polypropylene (PP/PE), Nominal pore diameter = 0.05 µm, porosity 45%, thickness 28 µm.		Commercial hydrophobic membranes, porous, hydrophobic and flat sheet	J. Mansouri, A.G. Fane, Osmotic distillation of oily feeds, Journal of Membrane Science 153 (1999) 103±120	
Celgard Inc. – Membrana Underlining Performance Industrial Separations (a Division of Celgard)			This business develops membrane contactors SuperPhobic® e Liquicel®		Europe Office: Erlengang 31 22844 Norderstedt, Germany Tel.: +49 4052 6108 78 Fax: +49 4052 6108 79 e-mail: Jschneid@celgard.net web site: www.liquicell.com www.membrane.com
Gore, W.L. & Associates GMBH		**Gore membranes** Reference pore size: 0.03 to 20µm. Wide range of air flows. Wide range of liquid flows. Hydrophobic and hydrophilic. Standard products: 0.05µm 0.1µm 0.2µm 0.45µm 1.0µm			Gore, W.L. & Associates GMBH Dichtungstechnik Wernher Von Braun Strasse 18 D – 85640 Putzbrunn – Germany Tel.: +49 (89) 46 1222 11 Fax: +49 (83) 46 1223 06 e-mail: ipd-deutschland@wlgore.com , processfiltration@wlgore.com website: www.gore.com
Donaldson Company Inc., Microelectronics Group	**Donaldson Company Inc., Microelectronics Group** Develops PTFE membrane				**Donaldson Company Inc., Microelectronics Group** Donaldson Europe B.V.B.A. Interleuvenlaan, 1 B-3001 Leuven, Belgium Tel.: 32 16 38 3811

					Fax: 32 16 40 0077 e-mail: LeuvenRD@mail.donaldson.com Tetratec-Europe@mail.donaldson.com Website: www.donaldson.com
OEM GE Nylon - Hydrophobic Membranes	Hydrophobic membrane is a pure polymer internally supported with an inert polyester web. It is a supported, hydrophobic nylon impervious to aqueous-based solutions making it ideal for use in venting applications. GE Nylon - Hydrophobic membrane is available in rolls up to 33 cm (13 inches) wide, as well as sheets, cut discs and pleat packs that can be customized to meet your application and size requirements. The GE Nylon - Hydrophobic membrane is manufactured on-site in GE Osmonics facilities.		-Bag vents -Bioreactor venting applications -CO_2 monitors -Fermentation air applications -Filtering gasses to remove particulate -Insufflation filters -Lyophilizer venting or inlet air -Spike vents -Sterile process gases -Transducer protectors -Venting gasses from sterile processes -Venting of sterile tanks -I.V. filter vents		

5.2 End users

(Describe the existing and potential end-users, other than those already listed in Table 2)

Existing end-users of membrane distillation technology are in the field of clean water production; potential end-users are in the following areas:

- sea/brackish water desalination;
- wastewater treatment and food processing (concentration of juices, any natural extracts from plants, and raw cane sugar);
- textile waste treatment that is contaminated with dyes;
- for the removal of trace volatile organic compounds from water and extraction of other organic compounds from dilute aqueous solutions;
- concentration of any aqueous solutions;
- biomedical applications (such as water removal from blood and treatment of protein solutions);
- separation of azeotropic aqueous mixtures such as alcohol–water mixtures;
- pharmaceutical waste water treatment and in areas where high temperature applications lead to degradation of process fluids.

6. Expert's brief final judgment on the technology

(maximum 5 sentences)

1) Membrane distillation is one of the few membrane operations based on a thermal process. The energy consumption therefore is, in principle, the same as the traditional evaporative process. Nevertheless, this operation might become one of the most interesting new membrane system just in the logic of process intensification. All the other properties of membrane systems (easy scale-up; easy remote control and automation; no chemicals; low environmental impact; high productivity/size ratio; high productivity/weight ratio; high simplicity in operation; flexibility; etc.) can in fact be present. This technology can be used practically in a large variety of industrial and bio-medical processes as for the purification, extraction, concentration (to very high values), final formulation of organic and inorganic species.

2) In principle MD might in perspective overcome not only the limits of thermal systems but also the ones of membrane systems such as RO or NF. Concentration polarization does not affect significantly the driving force of the process and therefore high recovery factors and high concentrations can be reached in the operation, when compared with RO process.

3) New and better membranes are necessary for a further industrial exploitation of this technology. Better design of the membranes and of modules, an overall better engineering, are other areas where progresses will have to be made as soon as possible. Interesting studies are already sponsored by national and international agencies in various industrialised Countries.

4) New amorphous perfluoro polymers are becoming available which might contribute to solve the problem of hydrophobicity. It is also important to recall the potentiality of MD in acting as a precursor of the membrane crystallization systems, another interesting new membrane operation very consistent with the process intensification strategy.

5) The possibility of using alternative energy sources, such as solar or wind energy, has been recognized and is today under testing also for large scale applications (see for example FP6 MEDINA and MEDESOL projects).