Journal of Membrane Science and Research 5 (2019) 76-82

Journal of Membrane Science & Research

journal homepage: www.msrjournal.com

Review Paper

Desalination Research and Development in Saudi Arabia: Experience of the Center of Excellence in Desalination Technology at King Abdulaziz University

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Article info

Received 2018-09-24
Revised 2018-11-22
Accepted 2018-11-22
Available online 2018-11-22

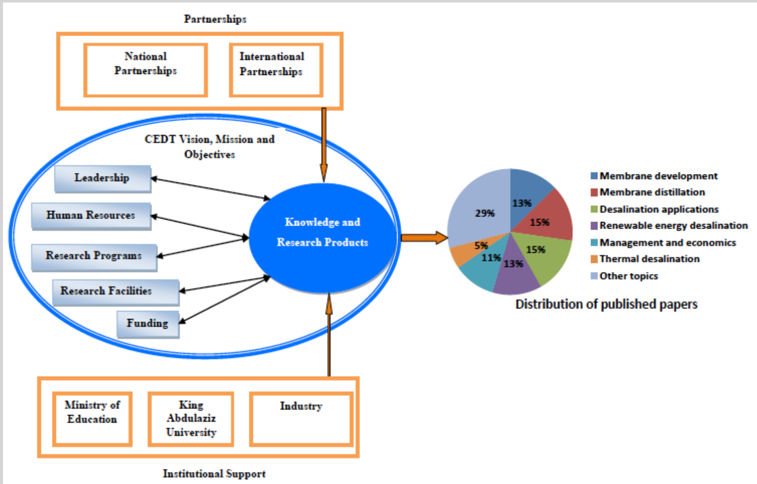
Keywords

Membrane preparation
PVDF
Membrane characterization
Membrane operations

Highlights

- Focus on the main research activities carried out at KAU-CEDT in Saudi Arabia
- Development and application of sustainable desalination by Membrane Process
- Recent results in the research activities in KAU-CEDT on Hybrid Polymeric Membranes
- Strong Research collaboration between CEDT and International Center (ITM-CNR)
- New CEDT Research matching the strategic objectives of The Saudi Arabia's 2030 Vision

Graphical abstract



Abstract

Membrane technology is growing very fast and it is used in several main applications from desalination, water and wastewater treatment to medical, biotechnology and gas separation field. Different membrane processes are applied depending on the applications from more traditional pressure-driven membrane processes (Microfiltration, MF; Ultrafiltration, UF; Nanofiltration, NF) to more advanced ones as Membrane contactors (Membrane Distillation, MD; Membrane Dryers; Membrane Emulsifiers) and membrane processes integrated with renewable sources.

In this contest, the development of innovative materials, as nanocomposite membranes as well as the study of innovative membrane processes, as MD, are part of the latest scientific research most of the universities and research centers are focusing their efforts on.These topics are also part of main research activities of Center of Excellence in Desalination Technology (CEDT) at King Abdulaziz University, Jeddah, Saudi Arabia and they will be described in details in next sections. CEDT is also involved in membrane processes and applications, renewable energy desalination, as well as computational modeling and simulation of membrane processes.

Contents

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DOI: 10.22079/JMSR.2018.94354.1217

1. Overview of R&D organization and drivers at CEDT

The Centre of Excellence in Desalination Technology was established in 2008 under the nation-wide Saudi Centers of Research Excellence (SCORE) initiative of the Ministry of Education. The Centre has set an ambitious multi-disciplinary research program covering the main areas of water desalination, which include membrane desalination, fouling and pretreatment, brine management, thermal processes, and solar-driven desalination. The aims of the main areas of research are summarized in Box 1. However, most of the research activities at CEDT have been focused on membrane related problems. The thrust on membrane processes is stemmed from the goals of the National Science, Technology and Innovation Plan (NSTIP), which envisages the expansion of the desalination capacity of the Kingdom must be matched with continuous efforts to strengthen the national capacity in the technical know-how on membrane preparation and membrane desalination technology. The NSTIP approach is towards the indigenization of membrane technology, not stopping merely at the process application using the commercially available membranes, but rather aiming for local development and preparation of specifically designed membranes.

The recent trends of the desalination industry in Saudi Arabia show that membrane desalination becomes a particularly attractive and promising technology for the Saudi economy and desalination industry. Large RO plants have been already commissioned or contracted in the country and the total share of RO desalination approached 20% of total capacity. The desalination capacity of the kingdom will be doubled within the next 10 years mainly through construction of new RO plants.

The Kingdom of Saudi Arabia quest for creating a knowledge-based economy supported by a strong industry base is further streamlined in specific industries of national importance such as the desalination technology. Hence, the government attracted leading desalination technology companies to localize manufacturing of important components through joint ventures with Saudi partners. Toyobo has launched its membrane manufacturing facilities on the Red Sea coast at Rabigh in 2014 in partnership with the ArabianJapanese Membrane Company, LLC. Oneyearlater, othertwo membrane industrygiants, Dow and Toray also have established their own factories on the Arabian Gulf coast at Jubail and Dammam, respectively.

The drivers described above promoted the CEDT vision, mission and objectives. The interactions between the main internal and external elements of CEDT business plan (Figure 1) are streamlined to lead towards essentially four categories of knowledge and research products.

Firstly, CEDT has emphasized to establish a substantial research infrastructure spanning from membrane synthesis and preparation, including a hollow-fiber spinning machine, to process application, with excellent membrane characterization facilities (Figure 2). The center has direct access to the Red Sea through its laboratory located at Abhor KAU campus and through its research station (under construction) at Rabigh KAU campus.

The expansion of the desalination and water industry market in Saudi Arabia should be matched with human capacity building programs to prepare high profile experts to meet the demand for this sector. CEDT is providing unique opportunities for developing and advancing the careers of the desalination industry professionals through short training courses as well as through postgraduate research projects (Table 1).

2. Approach to strengthen R&D at CEDT in view of the Saudi Arabia's Vision for 2030

Strengthening R&D at the Saudi research institutions will contribute towards the achievement of the strategic objectives and the initiatives of the National transformation program 2020 and the Saudi Arabia's Vision for 2030. Table 2 lists the strategic objectives of the Saudi Arabia's Vision for 2030 and how the R&D on membrane desalination will contribute to achieve benchmarks. Membrane technologies are the best available option for achieving the objectives of the Saudi Arabia's Vision for 2030 which aims to increase the usable water supply in urban areas through the treatment of impaired water sources, such as wastewater and brackish groundwater, for reuse in addition to the seawater desalination. Increased water reuse will substantially reduce the demand on desalinated water, therefore, simultaneously minimizing energy use in desalination plants and preserve financial resources which would be required for expansion of the desalination capacity.

To achieve the expectations of Saudi Arabia's Vision for 2030, CEDT should be prepared to overcome some main challenges and constrains and revise its business plan with emphasis on strengthening the relations with desalination industry. The following issues will be considered in this process.

Box 1. Aims of the main areas of CEDT Research Program.

Membrane desalination
- Development and optimization of novel membrane desalination processes
- Development of advanced simulation-based and experimental techniques and tools for the design of novel membrane modules
- Undertaking fundamental studies on membrane transport phenomena

Feed water pretreatment and membrane fouling
- Studying the phenomena of membrane fouling with particular focus on local Saudi seawater conditions.
- Developing new and improved methods to mitigate the effects of membrane fouling.
- Testing and optimize novel feed pretreatment processes.

Brine management
- Developing sustainable and cost effective brine management methods for inland and coastal areas.
- Developing appropriate technologies for production of marketable salt residues from brine streams.

Thermal desalination processes
- Developing innovative thermal desalination processes serving niche applications.
- Improving energy efficiencies of thermal processes through hybridization and new process alternatives.
- Developing software tools for effective process optimization and performance monitoring.
- Developing and evolving small scale thermal desalination applications

Solar-Driven Desalination
- Identifying and developing the best combinations of solar energy, energy storage, and desalination technologies for various scales of applications.
- Optimization of operation protocols for solar-driven desalination systems based on pilot-scale projects.

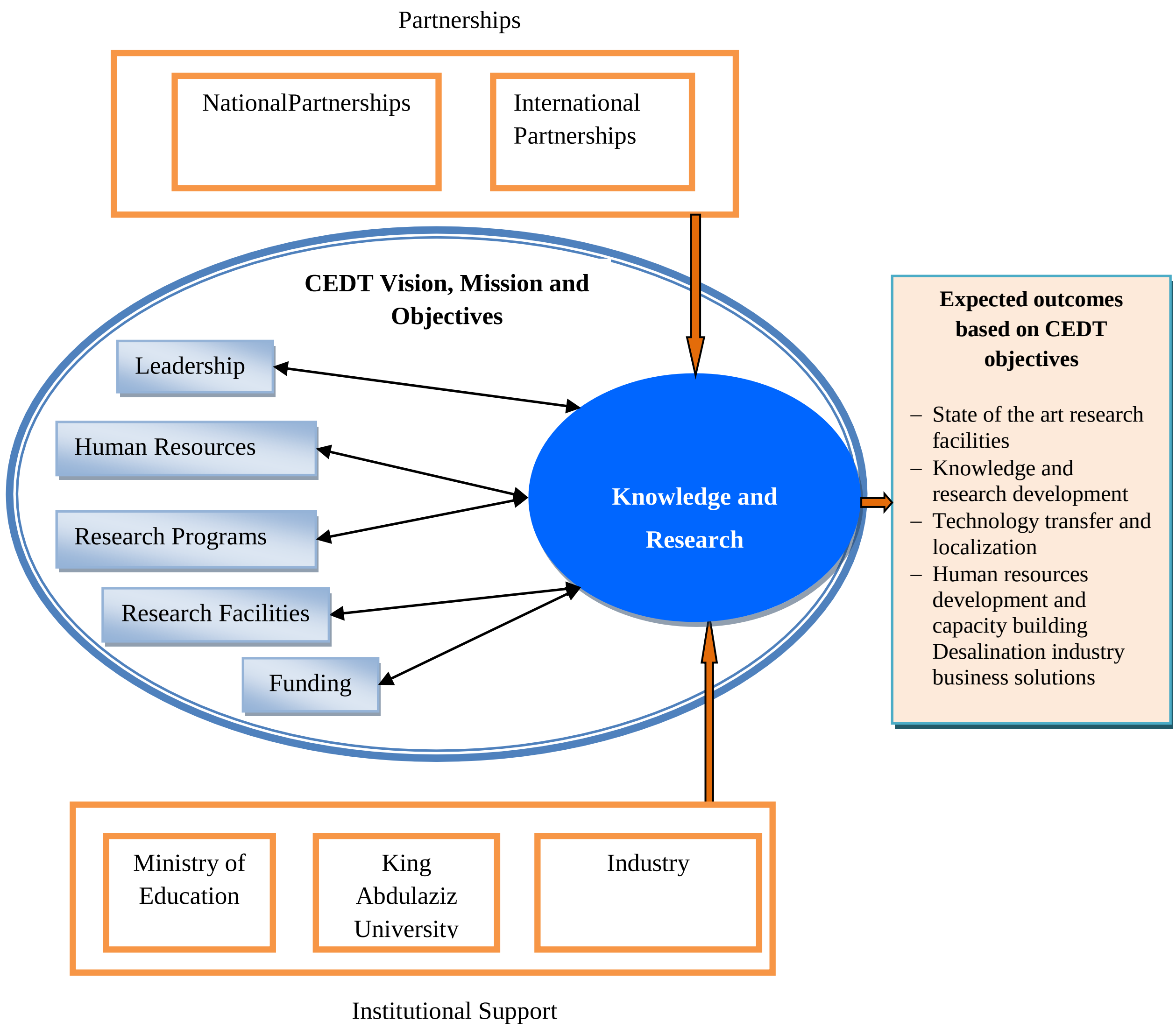


Fig. 1. Elements of the CEDT business plan.

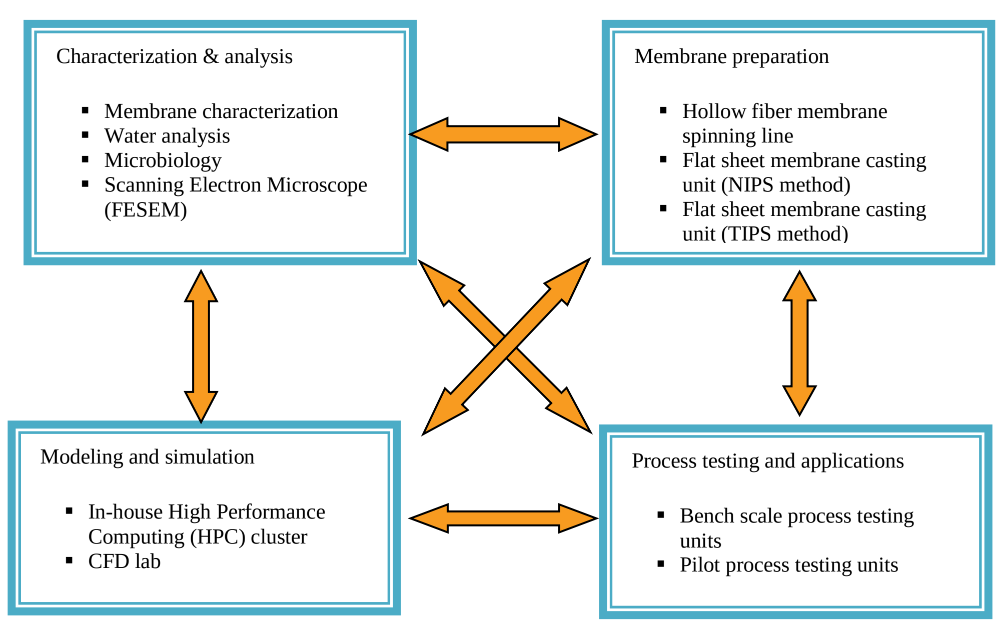
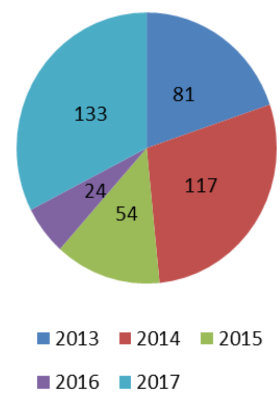


Fig. 2. CEDT research facilities.

Table 1
List of important training courses and workshops organized at CEDT till the end of Year 2017.

Training workshop title and date	Number of trainees per year
1. Applications of emerging membrane technologies for brackish and seawater desalination, January 2013	
2. Polymeric and inorganic membranes preparation and characterization, September 2013	
3. Advanced membrane desalination of contaminated brackish groundwater to improve Jeddah urban water cycle, November 2013	
4. Advanced topics in membrane engineering: Membrane contactors, reactors and integrated membrane systems, January, 2014	
5. Advances in membrane desalination technologies, May 2014	
6. Frontiers of membrane materials and membrane preparation techniques, February, 2015	
7. Emerging technologies of seawater and brackish water membrane desalination, February , 2016	
8. Process intensification strategy in desalination and water reuse , February, 2017	

Note. Most of training courses and workshops have been implemented by Prof. Enrico Drioli, Emeritus Professor of Chemistry at the University of Calabria, Founding Director of Institute on Membrane Technology (ITM-CNR), Italy, and Adjunct Professor, Center of Excellence in Desalination technology, King Abdulaziz University.

2.1. Promote the number of postgraduate students associated with the center

Postgraduate students are the backbone of research in research institutions. A positive correlation has been proven between the research productivity of any research institution and the number of postgraduate students enrolled. The statistics of the best research universities worldwide shows that the postgraduate to undergraduate students' ratio is in the range from 35-64% [1]. The Saudi research universities are still far behind with respect to this ratio with postgraduate to undergraduate students' ratio ranging from 5-14% only [2]. The association of postgraduate students with research centers within each university is also weak basically because of lack of sufficient number of students at the level of academic departments. For example, only 5 Master students and two PhD students have been associated with CEDT during the last five years. Hence, there is a need to develop a postgraduate programs model tailored for research centers to maintain a constant stream of postgraduate students associated with each center every year. This model may include specially designed multi-disciplinary Master and PhD programs developed in association with the relevant academic departments in the university. Scholarships and student bench fees shall be secured as well to insure smooth completion of the program of study for each enrolled student.

2.2. Build a sustainable framework for staffing and funding of the center

Leveraging human and financial resources is an important prerequisite for promotion of the research productivity of CEDT. An effective framework shall be developed to secure financial sustainability through supporting salaries of adequate number of researchers and postdoctoral researchers and expenses of research projects. Besides sustainability, the framework should allow fast and dynamic procedures for staff recruitment, approval of proposal of projects and procurements of research materials and equipment.

3. R&D activities on membrane systems at CEDT

A portfolio of diverse research projects have been carried out in CEDT which aimed to develop core competences in the areas of membrane development, membrane fouling, membrane distillation, membrane processes and applications, renewable energy desalination, as well as computational modeling and simulation of membrane. One of the keystone policies of CEDT is to establish a strong collaboration with leading national and international research institutions and prominent scientists to accelerate knowledge transfer in the field of membrane technology and its applications in desalination and water reuse. These projects focused on pilot testing of a membrane distillation unit, preparation of blended hydrophobic polyvinylfluoride(PVDF) hollow fiber and flat sheet membranes utilizing non-induced phase separation(NIPS) and temperature induced phase separation (TIPS) methods, preparation of fouling resistive polyethersulfone (PES) membranes through the incorporation of silver and cobalt nanoparticles in the membrane matrix and developing a direct measurement method for organic substances in seawater using quartz crystal microbalance method to control and predict fouling occurrence of SWRO membranes.

The research projects can be classified under three different categories based on funding source as:

i) Internal Projects;
ii) King Abdulaziz City of Science and Technology (KACST) funded projects;
iii) Research collaboration projects.

i) Internal Projects

Immediately after establishment of CEDT, few project proposals aligned with the different research themes of CEDT have been submitted by KAU staff and approved for funding using CEDT establishment grant. These projects represented the nucleus of the core research activities at the CEDT at its beginning years. The approved projects are based on modern technologies and contain some novelty in methods or modification in the existing body of knowledge from the standpoint of experimental or theoretical understanding. The topics of funded projects include solar energy assisted membrane distillation [3-5], humidification-dehumidification technique [6,7] and barometric desalination [8,9].

ii) King Abdulaziz City of Science and Technology (KACST) funded projects

Recognizing the limitations of CEDT establishment grant and for securing the sustainability of the research activities of the CEDT the researchers have been encouraged to submit research proposals for funding from external sources, mainly the King Abdulaziz City of Science and Technology (KACST), which is the main body responsible for research funding nation-wise. Only one project was funded by KACST under the National Science, Technology and Innovation Plan (NSTIP) on the design and testing of spacers for membrane separation modules [10-12].

iii) Research collaboration projects

One of the main strategies of CEDT is to strength and startstrong partnerships with leading national and international research institutions and top scientists to speed-up knowledge transfer in the membrane technology field and its applications mainly in desalination and water reuse. CEDT have been engaged in a collaboration research projects with Saline Water Conservation Corporations (SWCC) on investigating the potential use of membrane distillation to increase the recovery ratio and overall efficiency ofdesalination plants. Frequently, the researchers at CEDT are engagedin fruitful joint research activities in membrane engineering field with their counterparts from the Institute on Membrane Technology of National Research Council of Italy (ITM-CNR) [13-19]. The Hitachi Plant Technologies, Ltd., Japan was a CEDT partner in implementing an R&D project on real time measurement of RO membrane fouling [20,21].

4. Synopsis of CEDT R&D output

The outcomes of research and development activities at CEDT have been disseminated throughreports, peer reviewed papers in international journals, conference proceedings, presentations and patents. The distribution of peer reviewedpublications according to the topic of research is shown in Figure 3.

5. Membrane Development

In membrane operations, one of the main problems still to be solved for enhancing the membrane performance and the membrane life-time is the reduction of fouling and bio-fouling in particular in water, waste-water treatment and desalination. Several options have been tested for tackling this issue mainly acting on membrane process parameters, membrane module geometries and innovative membrane developing by using:*i.* innovative antimicrobial and antifouling coating, *ii.*loading antimicrobial and functionalized nanoparticles in polymeric membrane matrix.

In this direction, the research activities on the on-going collaboration between the Institute on Membrane Technology (ITM-CNR,Italy) and Center of Excellence in Desalination Technology King Abdulaziz University (KAU-CEDT) have been published in several international peer-review journals. They have been conducting on the production of innovative nanocomposite membranes, loaded with different types of fillers, for water-treatment and desalination applications [13, 15, 17-18]. Recently, a review on the nanocomposite membranes have been published critically discussing on the properties modification of the produced membranes by using different types of nanofillers, such as carbon nanotubes, zinc oxide,graphene oxide, silver and copper nanoparticles, titanium dioxide, 2D materials loaded in the polymeric matrix as well as on membrane surface [13].

In the first experimental work,Gzara et al. [15] reported a study on membrane preparation, without nanofillers, by using polyethersulfone (PES) and polyvinylpyrrolidone (PVP), as additive, for better evaluate the relationship between selected preparation conditions and membrane features which are important to tailor membrane morphology and properties depending on the target application. In particular, four selected variables such as polymer and additive (PVP), concentration, coagulation bath composition and timebefore immersion in the coagulation bath, have been considered. Membranes with different pore sizes, from 0.1 to 1.3 µm, and water permeability (from 30 to 250 L/m^{2}h) have been tailored by changing the coagulation bath composition (water and water/isopropanol), time before immersion (from 0s to 90s), PES concentration (from 13wt.% to 18wt.%). Moreover, membranes void fraction and mechanical propertiesshowed the typical trade-off, and were connected to theirmorphology. On the basis of these results, the PES membranes produced could find application in Ultrafiltration (UF) and Microfiltration (MF).In another work, Rehan et al. reported the use of flat PES mixed polymeric membranes filled with silver nanoparticles (AgNPs). The membranes have been produced by NIPS process using polyvinylpyrrolidone (PVP) andN-methyl-2-pyrrolidone (NMP), as additive and solvent,respectively, and adding up to 0.65% of AgNPsin the dope solution before casting [17].

The presence of the AgNPs as well as their good dispersion in the polymer matrix has been proved by several characterization techniques as FTIR-ATR, XRD and SEM. In particular, the produced membranes show typical asymmetric structure, a finger-like porous sub layerand sponge like active layer. The obtained asymmetric structurewas tailored increasing the AgNPs concentration, which allowed suppressing the finger-like porous structure due to a slow down of the demixing rate between solvent and non-solvent. Then, surface analysis by EDX, AFM and contact angle proved also the presence of the AgNPs on the membrane surface, the roughness and the hydropholicity (lower contact angle) increased. The water permeability, in the range of 40 to 200 l/m^{2}h, as well as the mechanical properties increased by the addition of the nanoparticle while the pore size dimension remained in the range of UF membranes (0.06-0.09 micron). Finally, the antimicrobial tests have been performed and pristine membranes showed a growing of E. Coli on their surface, vice versa a drastically reduction of bacteria was observed with the nano composites containing the AgNPs.

In another article, cobalt nanoparticles (CoNPs) were synthesized by the reduction of Co^{+2} in aqueous solutions using 4-aminophenol as reducing agent and cetyltrimethylammonium bromide (CTAB) as capping agent [18]. The nanocomposite membranes of PES-cobalt nanoparticles (PES-CoNP) have been prepared by NIPS, using NMP and PVP in different concentration, respectively as pore forming and dispersing agent (of the CoNPs) and pure water as non-solvent.Also in this case, the nanocomposite membranes have been characterized for determining the main features of the produced membranes. Similar to the previous work, the membrane structure was asymmetric with dominant finger type, once the PES membrane did not contain any NPs, to a more sponge structure at higher NPs concentration.The presence and homogeneity of the NPs in the polymer matrix were determined by FT-IR, XRD and EDX. The permeability tests with urban wastewater (rich in bacteria) and seawater(poor in bacteria) were performed. The results showed that the anti-biofouling activity was higher for urban wastewater than seawater and the higher concentration of NPs allowed to reduce the decrease in time of the flux due to lower propensity of the membrane to fouling.

Table 2
Relevance of the membrane desalination R&D to the Saudi Arabia's Vision for 2030

Strategic Objective	Key Performance Indicator	How membrane products contribute to achieve benchmark
Expand service coverage	Percentage of reused sewage water to be increased from 17 % to 35%	Membrane products are proved to be the best available technologies for sewage treatment
Boost water storage resources and security	Total available capacity (designed) of desalinated water to be increased from 5.1 MCM to 7.3 MCM/Day	Membrane products will contribute to increase the share of small scale water produces
Optimize the use of renewable water resources for agricultural purposes	Percentage of water used in the agricultural sector relative to total available renewable water resources to be decreased from 416% to 191% by 2020	Availability of low cost and efficient membrane products will promote utilization of brackish groundwater and treated wastewater for irrigation
Organizational Development and Privatization	Percentage of treated water production through strategic partners to be increased from 0 % to 20%	Membrane products will create a large number of small scale water users who depend on their own source of treated water and who can be regarded collectively as a strategic partner
Improve financial efficiency	Percentage of tariff to actual water cost to be increased from 30 % to 100%	The rise in water tariff will improve competitiveness and profitability of water produced by small capacity membrane products
Increase local content	Percentage of local content in capital and operational projects to be increased from 30 % to 40%	National membrane products will rely mostly on materials and components of national origin
Establish emerging technology companies with added value to contribute to the increase of local content	Number of tech-companies emerging from universities through the Innovative Companies Program to achieve a target of 800 companies	Availability of a national membrane product will promote the number of the Saudi tech-companies

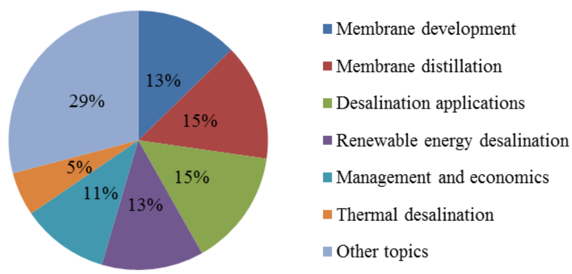


Fig. 3. Distribution of published papers by topic of research.

The emerging membrane processes such as membrane distillation require membranes that are not only having hydrophobic properties but also good and stable permeability, high rejection and acceptable durability. Research efforts have been dedicated to develop PVDF membranes using phase inversion method through blending a low molecular weight PVDF copolymer with a high molecular weight PVDF homopolymer at various polymeric concentration of dope solution and different solvents or mixed-solvents [14]. The underlying concept of blending is to optimize the mechanical strength properties which improve with the presence of PVDF homopolymer and the porosity requirement which improves with the presence of PVDF copolymer. Dope solutions having a higher concentration of homopolymer PVDF alone were found too viscous for easy membrane casting but when the homopolymer PVDF was blended with the copolymer PVDF the dope solution becomes less viscous and the porosity of the membrane improves.

6. Membrane distillation

Membrane Distillation (MD) is an emerging desalination technique which is characterized by its compactness, low operational hydrostatic pressure requirement, low working temperature and ability to desalinate highly saline streams [19]. Those features make it possible to be powered by renewable energy or any waste heat or low cost heat energy sources [22]. For example, it is known that the reject stream of MSF desalination plant contains a high exergy since the temperature of the MSF reject is above 45 °C. The recovery of this exergy will improve the energy efficiency of the MSF plant. However, the most distinct feature of MD is its ability to desalinate highly saline brines and wastewater. MD is the only viable option to increase the recovery ratio of MSF and RO plants due to its ability to treat feeds with high salinity and impurities.

The negative effects of temperature polarization phenomena in MD process can be mitigated by improving the flow thermo-hydrodynamic conditions through proper membrane module design and selection of optimal operating parameters. The channel spacers in plate-and-frame and spiral-wound membrane modules are an important design feature of the membrane module due to their positive effect on improving mixing in the direction vertical to the mean flow and negative effect on increasing the pressure drop along the channel. Al-Sharif et al. (2013) [11] applied the open source CFD code library OpenFOAM for 3D modeling and simulation of spacer-filled channel of MD membrane module considering three non-woven spacers with different geometrical features. The modeling aspects included model geometry, computational domain, choice of boundary conditions and discretizsation schemes. The geometry of spacers is characterized by number layers of filaments (double-layer and triple-layer),the diameter of the filaments, the angle of the filaments with respect to the flow direction, the spacing between the filaments, and the channel height. The impact of spacer geometrical features on temperature polarization and pressure drop have been established. The spacer type of 3-layer geometry with the wall-adjacent filament layers aligned with the flow direction was found to cause the lowest pressure drop while producing a robust symmetrical temperature profile, while the 2-layer flow aligned square spacer was found to be the least desirable design, producing asymmetric temperature and velocity profiles and high pressure drops.

The temperature/concentration polarization phenomena and pressure drop along a spacer-filled channel representing the case of DCMD spiral wound or flat plate modules were characterized experimentally. In fact the thermo-fluid dynamic efficiency of the membrane modules is dependent on these two parameters. Therefore one of the main goals in the design of an efficient MD membrane module is to minimize polarization by promoting turbulence flow regimes through the use of spacers with appropriate shapes and sizes and at the same time to minimize the pressure drop across the module length to avoid working at a higher operating pressure than the liquid entry pressure limits. The optimum flow and filament angles for the spacers were obtained experimentally using Thermochromic Liquid Crystal (TLC) temperature measurement technique by testing spacers with two layers of orthogonally arranged cylindrical filaments positioned at flow angles ranging from 0° to 90° [10, 12].Also, the effect of filament angles changing from 30° to 150° with 30° increments was studied while keeping the flow angle symmetrical. The spacers oriented symmetrical with respect to flow direction gave better results in terms of higher heat transfer rate but the pressure drop increased with increasing spacer's filament angle. The symmetrical flow attack angle $\alpha = 45°$ gave the highest dimensionless heat transfer coefficient (Nu).

The performance of a solar energy (thermal plus PV) driven DCMD pilot unit was evaluated as a function of the operating parameters [3,4]. The most significant operating parameters are the trans-membrane temperature difference and the fluid mass flow rates (hot and cold). The testing results indicated the inappropriateness of commercial hydrophobic membrane modules for MD pilot units due to low water productivity and high heat losses from the hot to the cold side. The effects of intermittent operation on the performance of the solar powered DCMD pilot unit were investigated in a follow up study [5].

The developed PVDF membranes at CEDT have been tested for further desalination of seawater reverse osmosis (SWRO) brine using direct contact membrane distillation (DCMD) [16]. The high salinity of the SWRO brine (55 g/l) resulted in a reduction in water vapor flux up to 50% less than water vapor flux when pure water was used as a feed. The cross flow rate effects on water vapor flux were found more predominant when the salinity of feeds is low.

7. Conclusions

The research and development endeavors of the Center of Excellence in Desalination Technology at King Abdulaziz University are driven by several favorable factors notably the quest of Saudi Arabia to be a leader in the development and application of sustainable desalination technology. Though CEDT adopted a research program of diverse topics most of the research activities have been focused on membrane desalination considering the recent trends of the desalination industry in the Kingdom. Also, the R&D activities of the Center are matched well with the strategic objectives of The Saudi Arabia's Vision for 2030, which include augmentation of water supply in urban areas through desalination and water treatment, capacity building, technology transfer and localization, and strengthening international collaboration. The CEDT will maintain in the near future the current research line focusing on development of blended fouling resistive polymeric membranes through the incorporation of nanoparticles in the membrane matrix, membrane modules design, membrane distillation applications and renewable energy desalination. The lessons learned since the launch of the Center indicates the importance of establishing strong international collaborations to accelerate knowledge transfer and improve quality of the research. Also, for maximization of research output it will be necessary to increase the enrolment of postgraduate students associated with CEDT R&D projects.

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