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Present Developments in the Design of SWRO Plants

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ABSTRACT

Over the past few decades, seawater reverse osmosis has become the most widely used desalination technology in many coastal regions around the world. However, the technology is associated with high-energy consumption and a biofouling phenomenon that occurs in membranes, which represent the two major shortcomings limiting its full implementation worldwide. As such, trends in technological development of the plants focus on reducing energy consumption and fouling potential of the systems. There are many research and development initiatives investigating feasibility and effectiveness of sustainable sources energy, particularly wind and solar power systems to run large- and medium-sized desalination systems. Other research initiatives are investigating possibility and viability of adopting nanotechnology to improve surface characteristics of membranes and consequently, minimize impacts of biological fouling on system performance. The current research will explore development trends in design of reverse osmosis membranes, innovations to enhance the overall design of desalination plants, innovations on energy supply, and innovations to control biofouling.

Keywords: SWRO plants, Reverse osmosis, Current innovations, Future innovations, Sustainable energy-run desalination plants, Nanoparticles

1. Introduction

Over the past few decades, seawater reverse osmosis (SWRO) has become the most widely used desalination technology in many coastal regions around the world. Faced with effects of global change on freshwater sources, many governments are embracing SWRO to desalinate seawater in an attempt to ensure sustainable freshwater supply. Today, SWRO is rapidly phasing out use of distillation technology in desalination of salty water, accounting for about more than half of installed desalination plants in the world. Despite its high salt elimination capacity, SWRO is associated with high-energy consumption, one of the major shortcomings limiting its full implementation worldwide. It is also associated with a biofouling phenomenon, which affect efficiency of SWRO plants by increasing pressure and deposition of chemical compounds in the pressure vessel (PV) that shorten operational life of PV membranes. As a result, many current technological innovations concentrate on enhancing energy efficiency of the plants and minimizing effects of biofouling on membranes. Energy efficiency developments focus on improvement of materials used in the PV, enhancement of the RO process, and use of sustainable sources of energy. In future, the technological innovations will follow the same path, as the two factors remain the major drawbacks that limit full exploitation of SWRO potential around the globe (Malaeb et al, 2011; Garcia et al, 2010).

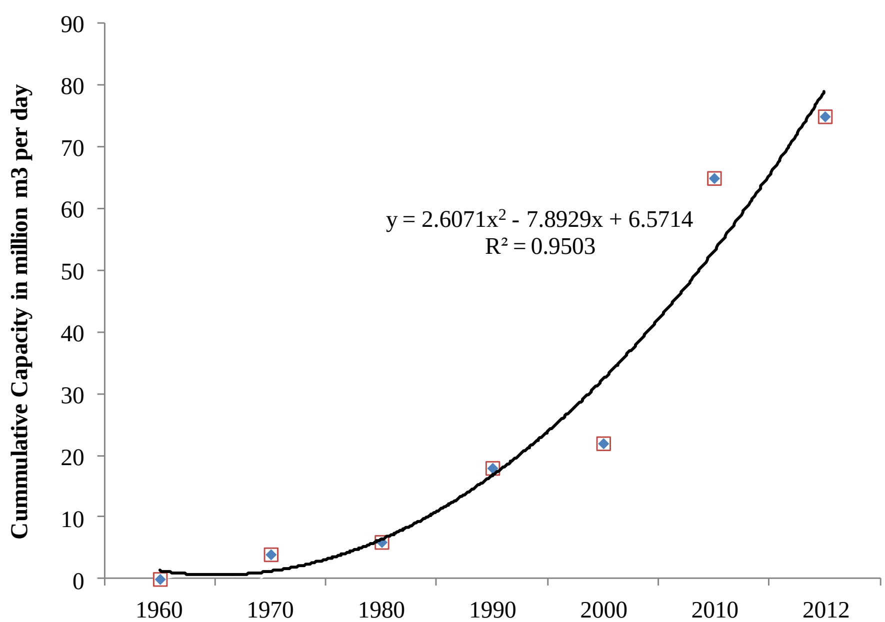

Fig. 1 Cummulative Capacity in million m3 per day of SWRO plants

The cumulative capacity increment shown in Fig.1 has shown the demand on SWRO on global basis. The capacity has also indicates that plants become attractive to the designer to record the incremental demand on SWRO. The current research will explore ongoing and future developments in the design of SWRO plants. The research will examine development trends in design of PV, innovations to enhance the overall design of SWRO plants, innovations on energy supply, and innovations to control biofouling.

2. Developments in Design of PV Membranes

2.1Past PV Membrane Technology

The PV forms the main unit of SWRO plants and it relies on membranes to purify seawater. Most innovations focus on improving the efficiency of the membranes without corresponding decrease in the salt rejection capacity of the plants. Currently, majority of SWRO plants rely on 8-inch spiral wound membranes to filter salt from the seawater. This type of membrane is the most preferred because it offers high salt elimination and high production capacities (approximately 47.5 m^3/d) with low energy consumption. However, some of its characteristics (for example, dimensions and layout) limit effectiveness of the SWRO plants. As a result, most of the current and future innovations in PV design concentrate on design improvements as well as layout and material modifications of membranes inside the main unit (Koch, 2010).

2.2 Improvents in the Design Characteristics of the Membranes

Manufacturers have been attempting to design membranes that can eliminate high proportions of boron concentrations from the seawater because of existing laws that require low levels of boron content in freshwater supplies. However, the innovation increases operational costs needed to implement RO-complementary technologies. Another major innovation in design of PV includes adoption of Hybrid RO membrane interstage design (also called internally staged design) technology. It allows use of more than one membrane from different manufacturers to cut down operational and maintenance requirements. For example, some SWRO plants (for instance, Las Palmas III plant) use membranes from different manufacturers (Malaeb et al., 2011).

There have been technological innovations to increase the diameter of the spiral wound membranes of the PV. The current 8-inch membrane has been associated with increased operational costs because it requires use of many elements, including pipes and connecting devices, among others. Some manufacturers of SWRO plant membranes recommend doubling the diameter to use 16-inch membranes in the plants. Others recommend a diameter of 18 inches for the membranes. The larger diameter membranes are associated with lower components (a fifth of that required by 8-inch systems), lower costs of installation and operation (half of costs associated with 8-inch plant), and high production capacities (about 400 percent of productivity of 8-inch plant). However, these innovations are yet to be implemented because they are currently being used for demonstration purposes only (Koch, 2010).

Improvement in the literature were statistically collected and scored to show that progress and development in the design characteristics of the membranes were moving positively towards better cost and productivity. Tables (1) summarize the % of improvement in the membranes since 1980 till 2010. The cost of the modules as it is shown in the table has decreased by 46% compared to the early 1980 where the membranes are so expansive. The performance of materials had also increase due to mass production and influence of research and development in the field.

Table 1 The Productivity, Materials, and, Costs

	1990	2000	2010
Productivity	+7	+12	+23
Materials	+5	+19	+28
Costs	-11	-32	-46

The cost of desalination has fallen during the past years, but it remains a costly water-supply alternative. Desalination facilities are being proposed in locations where considerable cost-effective conservation and efficiency improvements are still workable. The water planners and project managers must comprehensively analyze all opportunity, including conservation and efficiency, and pursue less costly, less environmentally damaging alternatives. Desalination facilities should be accepted only where water organizations have implemented all cost-effective water conservation and efficiency instrument. Desalination costs are influenced by many factors, making comparisons difficult and estimates uncertain. All cost estimates should clearly state the underlying assumptions. Cost comparisons must be done and studied a comparable basis so conclusion would be explicit.

2.3. Innovations to Enhance layout of Membranes

Synthetic polymers are manufactured by polymerisation of a monomer (condensation or addition) or by the co-polymerisation of 2 different monomers. The yielding polymer could be either a long, linear chain, such as linear polyethylene, or, a branched chain, such as polybutadiene, or, a three-dimensional highly cross-linked structure, such as phenol-formaldehyde, and, moderately cross-linked structure, such as butyl rubber. Initially, the plants relied on more than one stage configurations, with every stage operating a single activity in the overall desalination process. Today, the design has been reduced to a single-stage layout, with the PV being divided into several units called racks. Fig. 2 summarizes the type of polymers used in recent years in desalination plants.

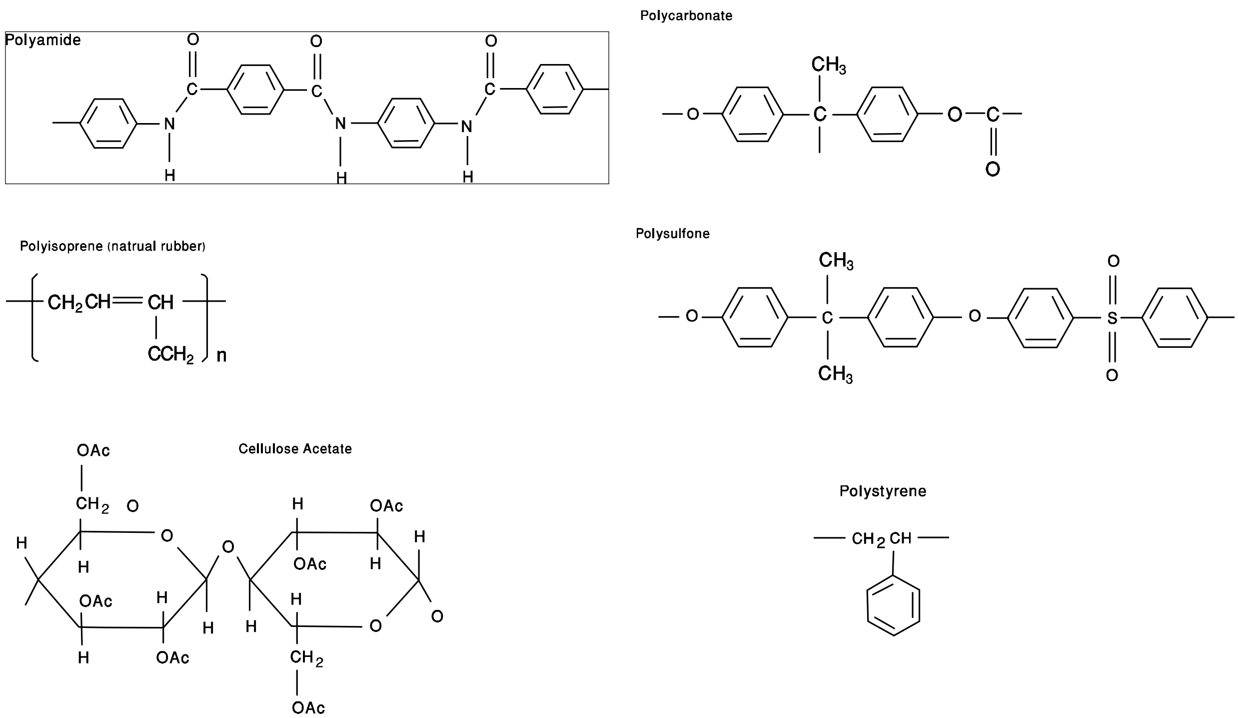

Fig. 2 The types of polymers that almost used in Desalination plants membranes

Many SWRO plants today are divided into seven or eight racks. The higher the number of the racks, the greater the benefits that include high flow rate of feed water and low capital cost. Currently, manufacturers are considering introduction of a PV layout with nine racks in the future. Division of PV into various racks necessitates adoption of different interconnection technologies to connect the endcaps of the membranes (Hydrunautic, 2012).

Over the years, the plants have been relying solely on coupler technology to interconnect the caps. However, the technology has been associated with poor quality of product and elevated costs of operation due to frequent leakages from O-rings used to couple the membranes. Recent innovations have attempted to eliminate the leakages by enhancing the efficiency of the O-rings. Among others, some of the major developments include the iLEC^{TM} technology and vented seal carrier design.

The iLEC^{TM} technology relies on a longitudinally-compressed O-ring seal as well as an arrangement of gyratory and longitudinal or transverse mechanical connector to couple the membranes directly. It also uses interlocking tabs around the circumference of every ABS plastic-based endcap to offer a tight seal on the O-rings. The technology eliminates operational and installation defects in O-rings, thereby reducing wear and tear of the rings, leakages, and backpressure from the product. Lately, Nitto Denko Corporation introduced a vented seal carrier design that integrates a set of vents intended to reduce occurrence of pressure imbalances on the various RO membranes. In future, special feed spacers can also be integrated into the RO membranes to prevent pressure drops. In contrast to conventional spacers, the future spacers will consist of a wide feed channel opened at the cross-section face to limit biofouling in the membranes and thereby, eliminate the need for frequent cleaning of the RO PVs (Hydranautics, 2012).

2.4 Design to Improve Materials for Membranes

Majority of PV components are made from polymeric materials due to their limited chemical activity in seawater environments and good permeability properties. Future innovations may involve use of nanocomposite materials in form of thin films (Lin, 2010). From Table (2) It is clear that reverse osmosis membrane material has received less innovations in the design of the materials but the treatment of the fluid has kept the pace towards more innovations and polymeric materials production,

Table 2 Type of polymeric materials that used for seawater desalination systems

Material	**Micro Filtration**	**Ultra Filtration**	**Nano Filtration**	**Reverse Osmosis**
Cellulose acetate	X	x	x	x
Polycarbonate	X			
Cellulose nitrate	X			
Cellulose esters	X			
Polyacrylonitrile		x		
Poly (vinyl chloride)	X			
PVC copolymer	X	x		
Poly (vinyl alcohol)	X			
Aliphatic polyamide	X	x		
Polypropylene	X			
Polysulfone	X	x		
Polyetheretherketone (Peek)	X	x		
Polyester	X			
Aromatic Polyamide	X	x	x	x
Polyethylene	X			
Polyetrafkuoroethylene(PTFE)	X	x		
Poly (vinylidene difluorude) (PVDF)	X	x		
Polydimethylsiloxane (PDMS)				
Polyimide	X	x	x	x

3. Innovations to Enhance Overall Design of SWRO Plants

3.1 Improve Efficiency of Power Recovery Components

These innovations focus on improving the overall efficiency of the RO technology by enhancing efficiencies of SWRO components other than the PV unit. One major innovation has been use of technologies to minimize power consumption in the pumping system of SWRO plants. Among others, they include utilization of variable-frequency pulley and belt systems, high booster pumps, and high-pressure pumps. Retrofitting of Pelton turbines presents another innovation being used to minimize energy requirements of SWRO plants (Penate et al., 2011).

3.2 Improve Efficiency and Recovery Production of Two-stage systems and introductory to the third stage

Today, plants with racks are being designed to ensure that the first pass of the feedwater results in high production capacities in order to reduce consumption of high energy during the second pass of the permeate. Other plants are relying on split partial layout to improve efficiency of RO by collecting filtered water from separate sides of the PV unit, thereby allowing a small proportion of product water to pass to the second stage of RO. Other systems use Permeate Throttling system between the first-stage and second-stage racks to prevent flux of filtered water in the second stage. The system consists of a control valve that regulates the backpressure in the PV unit with respect to changes in salty content or temperature of the feed water. Other plants rely on a brine conversion system at the second stage to ensure maximum recovery system. The system can recover extra product for upturns approaching 60 percent without substantial variations in salinity of the product (Alarcón-Padilla et al., 2010). Extra attention were given to add more stages in the product stages and implementation of third stage is now in the simulation process of calculation to further permeate production towards higher purity of water.

3.3 Innovations to Enhance Desalination Technology

Some of the potential innovations being considered to improve RO process include use of Nano-Filtration (NF) membranes for large SWRO plants and utilization of forward osmosis. Currently, SWRO plants (regardless of size) rely on Ultra-Filtration and Micro-Filtration membranes for the pretreatment purposes. However, their use in large plants results in some problems because of incompatibility of elements of the two membrane systems. Although its use is not widely accepted in SWRO systems, NF presents a better solution for large plants because it can work without the need to combine with any other conventional membrane. The market become attractive for nanotechnology as it is widely disperse and coverage to move swiftly to reduce the design burden and operation on the feed water side aiming to reduce silt density index (Fig. 3).

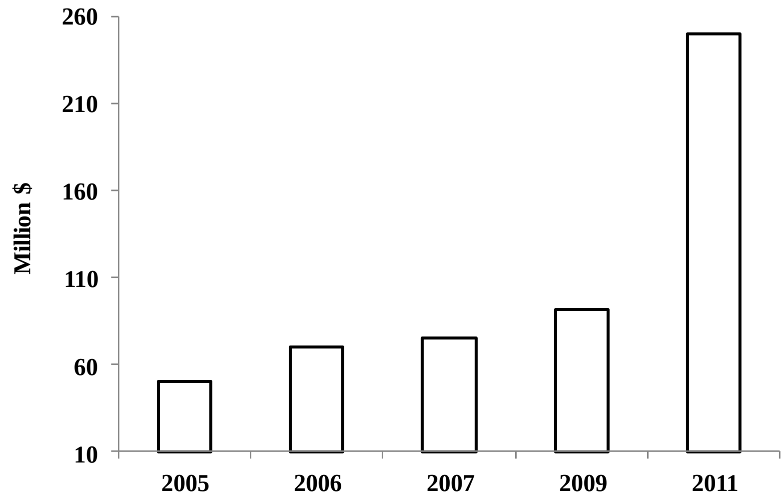

Fig. 3 Global Market for Nanofiltration for Water Treatment

The global market for nanofiltration membranes increased from $89.1 million in 2006 to reach $250 million by the end of 2011. It continued growth in regulations aimed at protecting the environment which positively affect the future expansion of the nanofiltration membranes market.

Manufacturers of RO systems are considering introduction of forward osmosis technology to replace RO technology in desalination systems. Based on its effectiveness in medical and food industries, the technology has potential to improve salt rejection capabilities of seawater desalination plants with lower energy requirements and reduced rates of biofouling. Other future innovations include use of emerging cleaning and anti-scaling chemical agents (WDR, 2010).

4. Developments in Power Supply of Large and Medium SWRO Plants

Over the years, fossil fuels have remained the principal sources of energy for SWRO plants around the world. However, adverse impacts on environment and public health associated with the fuels have compelled manufacturers and operators to turn to alternative sources of energy, which are regarded as environment-friendly. Today, some manufacturers have started using renewable energy sources, particularly wind energy and solar power systems to power small-scale plants in what has come to popularly referred to as Renewable Energy Sources – DESalination process systems (RES-DES). Research is also underway to investigate feasibility of these two sources to provide power for medium- and large-scale plants (Charcosset, 2009). Fig. 4 indicates the reduction in seawater power consumption for the production of 1 m^3 and it is obvious that the reduction was remarkable in the field which benefited the production cost to lower final economics of permeated water. Energy recovery is one of the major important issues related to sea water reverse osmosis plants that consume most of the energy to overcome the osmosis and produce permeate.

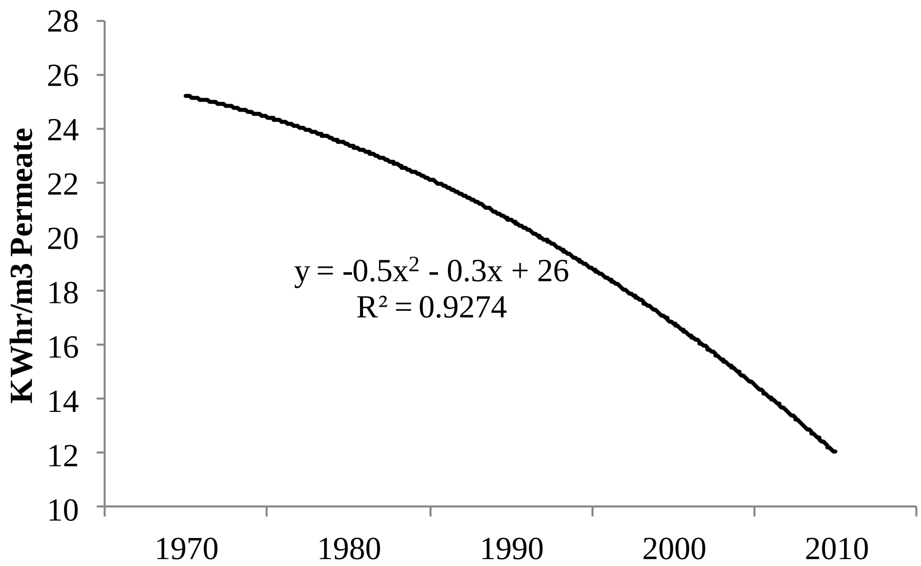

Fig. 4 Reduction in SWRO power consumption for the Production 1 m^3 permeate during 1970-2010

Table 3 shows the reduction occurred during the past five years in the energy recovery of desalination plants using sea water reverse osmosis. Energy recovery devices have become essential to SWRO operations, primarily because they significantly reduce energy consumption in these systems. Rotary isobaric devices provide a unique combination of isobaric and centrifugal features with high energy transfer efficiency, no maintenance, and easy operation.

Table 3 % reduced in the last 5 years in SWRO specific energy of (kW h/m^3)

	Small System	Large Conventional System	Large Low Energy System
Pelton Turbine	15	18	21
Turbocharger	22	21	21
piston Isobaric	-	23	17
Rotary Isobaric	23	19	19
Pressure Exchange	19	23	22

4.1 Development in the use of Renewable Energy for SWRO Plants

Of the two sources, wind energy has received wider acceptance as an alternative source of energy for the plants. It can be used to provide mechanical or electrical power for the desalination plants although it has been used widely as source of mechanical energy for high-pressure pumps in majority of small-scale plants. For medium or large plants, wind power presents the best alternative to fossil fuels as a source of electrical power (Vrouwenvelder et al., 2010).

Solar photovoltaic systems is another issue that are currently in use in small SWRO plants, with various solar-thermal power technologies being evaluated to test their feasibility for application in small, medium, and large desalination systems. One of the solar-thermal systems under development includes solar organic system, which uses organic solution as the working fluid and runs on the Rankine cycle (Fig. 5).

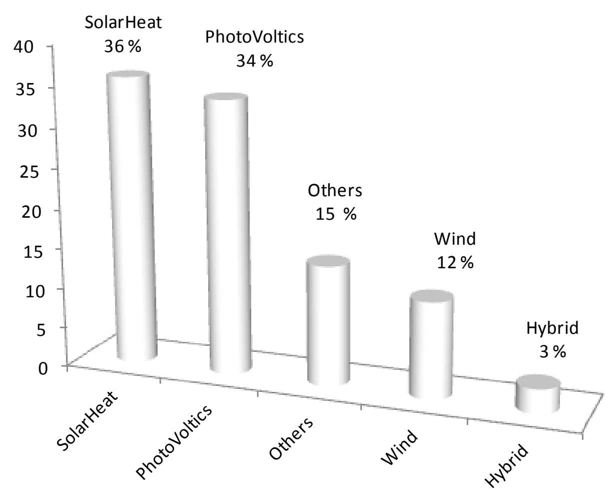

Fig. 5 Global Renewable Energy for Desalination (2010)
based on 160 operating plants

Compared with other existing solar-powered distillation systems, the Rankine cycle-based solar system presents the best source of power for medium plants. Other potential solar-thermal technologies for medium and large SWRO systems include solar membrane distillation and solar thermal power integrated with multi-effect distillation system (Subiela et al., 2009). Compared to wind power, solar energy systems have not gained wider acceptance in desalination systems because they require substantial capital and large sizes of land for installation (Charcosset, 2009).

5. Innovations to Control Biofouling

5.1 Biofouling and its Effects on Performance of SWRO Plants

Biofouling remains the major challenge facing operation of desalination plants around the world. It refers to unnecessary formation and bioaccumulation of microbial cells (commonly called biofilms) and extracellular polymers (excreted by the cells) on the surfaces of membranes and other SWRO module components. It occurs through various stages, starting with induction that involves deposition and formation of a plateau of microbial cells on membrane surfaces. Next, exponential growth stage ensues where the cells rapidly accumulate on the surfaces, forming biofilms. This is followed by a plateau stage in which the bioaccumulation of the cells becomes worse, completely changing the surface characteristics of the membrane and other RO components. Consequently, it affects negatively performance of the membranes by lowering effectiveness of convectional processes, pressure of the feed brine, and pressure of transmembrane system as well as increasing frictional forces within RO fluids. In turn, these effects lead to reduction in system productivity as they reduce surface permeability and salt rejection capacity of the membranes. As a result, various innovations are currently available to control biofouling and other developments are still being considered for use to prevent the problem (Herzberg et al., 2009).

A cleaning cycle generally includes several stages: product removal, rinsing with water, cleaning in one or more steps, and rinsing with water. In order to obtain a good cleaning effect, cross-flow velocity should be higher and the pressure lower than those used during normal operation. A typical cleaning procedure consists of the following steps that are applicable for the most but modified to reach the following during the past 5 years as it shown in table (4):

- Low flow pumping of the pre-heated cleaning solution at minimum pressure equivalent to 0.5 of osmotic pressure
- Recycling of cleaning solution until a stable temperature is achieved. In this stage, pH can be adjusted when necessary but reduction of the solution temperature is a must.
- Soaking the RO membranes with the cleaning solution for 1 to 10 hours, depending on the type and grade of fouling that should be monitored. This should be followed by high flow operation to flush the solutions out of the system.

Table 4 summarizes the most suitable, usual cleaning agents to the type of fouling.

Type of fouling	**Chemical agent**
Colloidal	NaOH solutions, chelating agents and surfactants
Organic	NaOH solutions, chelating agents and surfactants
Metal oxides	Citri acid with low pH or $Na_2S_2O_4$
Silica	NaOH solutions with high pH and preferred detergent monomers
Carbonate scales ($CaCO_3$)	Citric acid or HCl with low pH
Sulphate scales ($CaSO_4$, $BaSO_4$)	HCl solutions or sequestration agents (EDTA)
Biofilms	NaOH solutions, chelating or sequestration agents, surfactants and disinfectants using either hydrogen peroxide or sodium bisulphite

5.2 Trends in Biofouling Control Technology

5.2.1Pretreatment of Feedwater

For years, pretreatment processes have remained technology of choice to prevent biofouling in SWRO membranes and other module components. The processes aim to limit likelihood of fouling by eliminating the possibility of deposition of inorganic substances as well as filtering out biological contaminants from the feed water before it is introduced to the plants. Processes can be classified into two: micro-filtration or ultra-filtration membrane and traditional. Table (5) shows the improvement percentage in the pretreatment of feed water entering seawater reverse osmosis and it shows that improvement move positively in the recent years due to the perception of the importance of pretreatment to the desalination plants.

Table 5 % improvement measured from literature
(basis 150 literatures since 1985)

	1990	1995	2000	2005	2010
Improvement %	12	18	25	29	38

The latter processes, such as granular activated carbon filters involves various components, including granular and dual media filters as well as coagulation and floatation of dissolved air elements. Membrane processes are more advantageous than traditional ones because they can achieve minimal levels of silt density index and do not use substantial amount of chemicals and space (Vedavyasan, 2007).

5.2.2Use of Anti-Biofouling Chemical Agents

Use of anti-fouling chemicals (or biocides) presents another technology that has been in use throughout the history of SWRO plants. They are mainly used during pretreatment to reduce feedwater's potential of biofouling. They can be introduced occasionally or incessantly into the feed water using a metering device to control their concentrations. In addition, the chemical agents can use during downtime or shutdown of desalination plants or during shelf life of membranes and other elements to preserve them. Among others, the commonly used agents include chlorine and its compounds (such as chlorine dioxide and monochloramine) as well as ozone and sun's ultraviolet radiation. However, ozone and chlorine compounds are known to interfere with integrity of polymeric membranes through chemical attack and oxidation. Chemicals can also be used for cleaning or removing the biofilms from the membranes (Kim et al., 2009).

Table (6) summarizes the improvement in the anti-biofouling from 1985-2010. It looks that the innovation of antifouling due to better design progressed after year 2005 as it becomes obvious that the need to produce better quality of treated feed water introduced to the desalination part using membranes. The advantage of progress development in the biofouling helps to prevent membranes from declination in the production of permeates. Plants stopped and shutdown several time and membranes goes under cleaning because such phenomenon and improvement in the bioufouling agents supports the availability of the plants all the year.

Table 6 % Improvement in the statistical dispersion of Anti-Biofouling Chemical Agents in the literature (150 published papers)

	1985	1990	1995	2000	2005	2010
Dispersion in the market	3	4	6	8	22	29
Reduction in the Cost	6	9	12	16	32	42
Improvement in the efficiency of anti biofouling	2	2	15	18	29	34

5.2.3Improvement of Membrane's Surface and salt rejection

Modification of properties of surface membranes has gained attention as an effective anti-biofouling technology only recently. Studies are underway to determine effectiveness of various nanomaterials in enhancing the ability of membranes to prevent bioaccumulation of microbial cells on their surfaces. Potential nanomaterials under investigation include silver compounds, titanium dioxide, and carbon nanotubes. Used in conjunction with UV, laminated membranes made up of aromatic polyamide layers sandwiched in titanium dioxide particles have been shown to reduce growth of microbial cells significantly. Membranes impregnated with nanoparticles of silver and its compounds prevent growth of cells by inhibiting replication of DNA. Research in effectiveness of carbon nanotubes to prevent fouling in SWRO membranes has not yet received much attention owing to its mode of inhibition activity (Mahendra et al., 2008). Fig. 5 shows the status of design and improvement in the salt rejection of the membranes since 1980 which states how innovations contributed to the cost of produced water with high salt rejection. It is clear that the number of modules was reduced and cost of membranes eventually reduced accordingly due to the design stage of calculation.

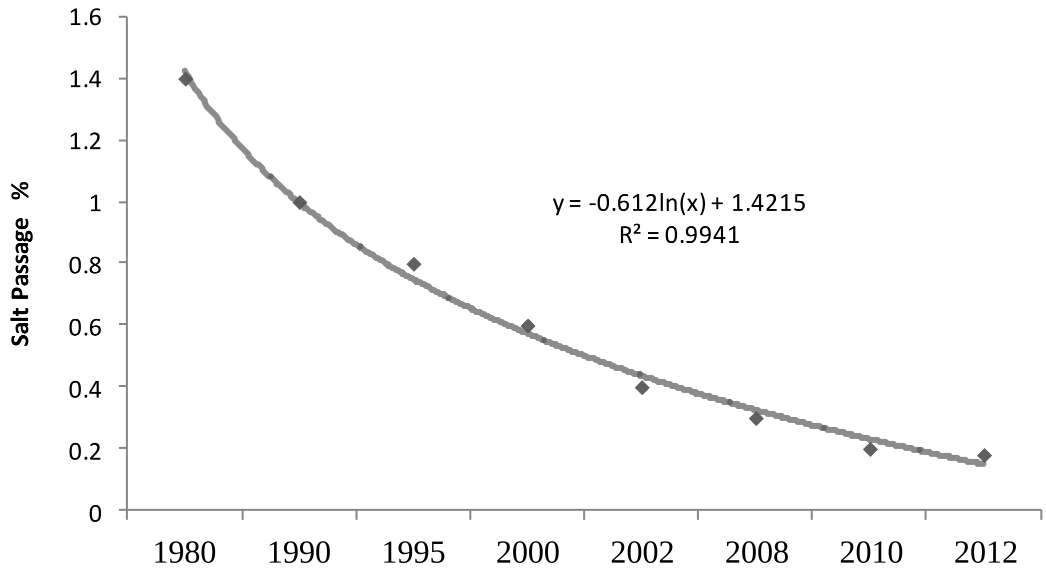

Fig. 5 Improvement in the % Salt Rejection Since 1980

6. Conclusion

Trends in design of SWRO systems focus on enhancing power efficiency of the systems and inhibiting bioaccumulation of microbial cells on RO membranes and other elements. Energy efficiency innovations concentrate on upgrading materials used in the PV, enhancing desalination process, and use of alternative energy sources. Biofouling mainly affects RO membranes, which consequently results in reduced salt elimination potential and permeability properties of the membranes as well as increased fluid viscosity. Various technologies, such as use of anti-fouling agents and pretreatment processes have been implemented to control the phenomenon, and others (for example, impregnation of RO membranes with nanoparticles) are being investigated for possible application in future. Use of the nanoparticles presents an effective way that would see the problem of biofouling in SWRO plants addressed effectively in future. However, the technology needs to be refined to address some of the associated shortcomings before it could be applied effectively in the plants worldwide. For example, there is a need to address chemical degradation associated with titanium dioxide-based membranes, and short-lived retention of silver nanoparticles in membranes, among others. There is also need to carry out research on other surface improvement technologies, such as use of membrane coatings, which have significant potential to inhibit bioaccumulation of microbial cells on surfaces of SWRO membranes. Moreover, research on effectiveness of combining two anti-fouling technologies may also be necessary to find another potential mechanism to address the issue of biofouling.

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