A Review About Membrane-based Water Desalination

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ABSTRACT

Water desalination plant - namely a process utilizing membrane technology – is under the scientists› current spotlight since it is such a promising solution for an imminent water shortage. Amongst several membrane water desalination methods, reverse osmosis (RO) has been the most often used process due to its considerably low energy consumption. There is also an ongoing development for the membrane distillation process (MD), a highly eco-friendly process in handling the rejected brine solution regardless of the feed solution concentration.

Similarly, each different desalination plant has distinct characteristics. Because the hybrid plants make up for the disadvantage of each plant, there should be extra concentration on the hybrid plants such as reverse osmosis (RO) & nanofiltration (NF) hybridized plant and reverse osmosis (RO) & forward osmosis (FO) hybridized plant. Due to the imminent environmental issues nowadays, the future development of the hybrid system and the desalination plant overall should place the impacts of the plant on the environment as the priority.

1. INTRODUCTION AND OBJECTIVES

Water desalination is a process of removing salinity from saline water and converting it into freshwater with low salinity[1]. Since water is no longer a symbol of abundance, desalination of seawater and brackish water is becoming an important technology to address the scarcity of freshwater resources in the world. The water crisis is imminent, causing "over 2 billion people experience high water stress" and "about 4 billion people experience severe water scarcity during at least one month of the year"[2]. From the 1950s, the world water usage has steeply increased from 1.2 trillion m^3 to 4 trillion m^3(Fig. 1)[3]. Especially in Cape Town, the reservoir water level is still only one-fifth of its capacity. Isabella Martin from *UC Berkeley's Master of Development Practice* claimed that "What Cape Town is now is a stark warning to the rest of the world. Plan now or your city will be next."

To take action for the water shortage, several countries are already adapting water desalination to obtain fresh water from the seawater. Especially, in gulf countries, water desalination is the main source of freshwater.[4] For instance, in Qatar and Kuwait, they have already been 100 percent reliant on desalination for their domestic and industrial freshwater needs.[5]

Before, the water desalination using a thermal distillation was the most popular method of water desalination. However, after a recent development of technology, water desalination that uses membrane technology, namely reverse osmosis, has been the most used method due to its lower energy consumption[6]. Up to date, about 50% of desalination plants are RO desalination plants[7].

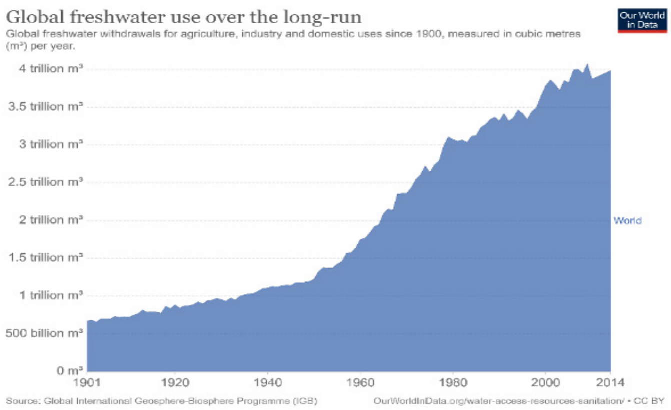

Fig. 1 Global freshwater use over the long-run[3]

Moreover, nowadays, as the nanotechnology is one of the main areas of scientists' research, membrane desalination using nanofiltration is also under extensive research of the scientists.

In this paper, due to the abundant usage of the membrane desalination processes, a brief review on the membrane-based desalination processes would be proposed. As the membrane-based desalination is the most frequently used technique worldwide, I firmly believe that the review on this specific desalination process will provide the community with a deeper insight about the technique and enable the community to compare and contrast several methods which are under the strand of the membrane desalination process.

As such, there will be a review about reverse osmosis (RO), membrane distillation (MD), forward osmosis (FO), and nanofiltration (NF). The paper will discuss the characteristic of each method. Then, there will also be a comparison of each method in the aspect of energy requirement, cost, and environmental impact. With the comparison, the paper will summarize the pros and cons of each method and provide future research that could be conducted to further improve the review of this paper.

2. REVERSE OSMOSIS (RO)

Reverse osmosis is generally used in desalination due to its lower energy consumption[6]. It operates in a way by applying an external pressure across the membrane (Fig. 2). Thus, the water is forced to permeate through and filtered by the membrane. It is in charge of about three-quarters of total desalination capacity with along its application in seawater desalination and brackish water desalination[8].

There has been a recent application of reverse osmosis with its combination with low-pressure membrane technologies such as ultrafiltration (UF) or microfiltration (MF). These combinations are often used for purifying the secondary wastewater.[8]

The most comparable technology with RO desalination is electrodialysis (ED). Electrodialysis is a better method of desalination than RO for low ion concentration. Thus, it can offer advantages over RO and is used in the industrial sectors to desalinate dilute aqueous or organoaqueous solutions. However, ED requires a high energy consumption at higher ion concentration. Hence, ED is rarely used for seawater desalination. (Fig. 3)

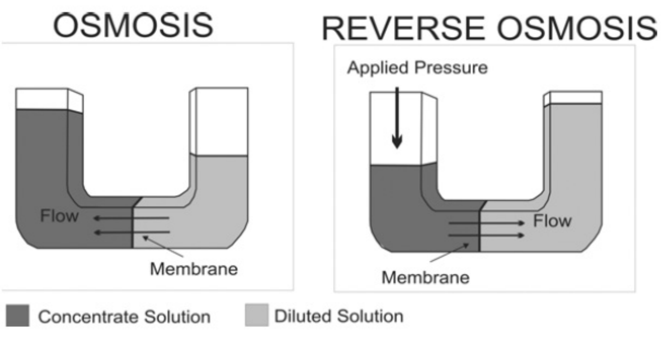

Fig. 2 Reverse osmosis principle (source: Aqualyng). Left: osmosis; right: reverse osmosis.

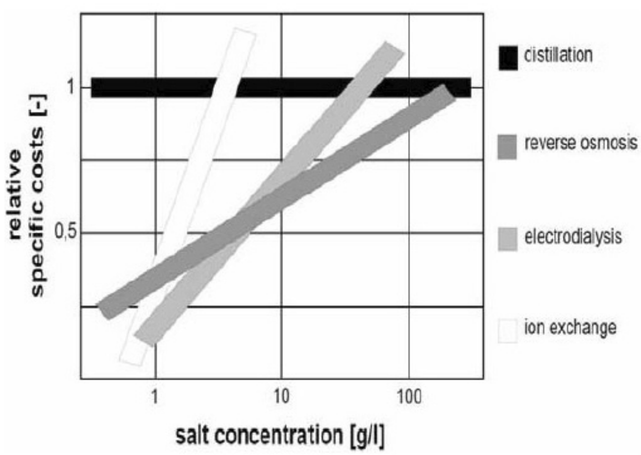

Fig. 3 Relative water production cost of reverse osmosis, distillation, and electrodialysis.[9]

2.1 ABOUT MEMBRANE

The first RO membrane introduced in the world was cellulose-acetate (CA) membrane.

However, the membrane deterioration by hydrolysis was the biggest problem of this membrane. Membrane deterioration is strongly related to pH and happens much faster under acidic or alkaline conditions[9].

To solve this problem, the next membrane was made of an active layer from polyamide and porous support of different material, polysulphone. The combination of these two materials made the membrane much more stable in both chemical and physical aspects. As a result, the membrane became strongly resistant to bacterial degradation and hydrolysis, and less influenced by membrane compaction. However, these enhanced composite membranes also have some disadvantages. They are less hydrophilic, which makes them have a stronger tendency for fouling than CA membranes. Also, they can be deteriorated by very small amounts of free chlorine in the feed stream[8].

Membranes nowadays are generally flat sheet membranes in a spiral wound module configuration. It has a good balance amongst permeability, packing density, fouling control and ease of operation[8]. To clean the membrane, usually chemical treatments are utilized. But sometimes, direct osmosis method can be used. When the salt concentration of the water increases, reverse osmosis shifts to direct osmosis, leading to a permeate backwash stream[10]. This is a relatively novel procedure for RO membrane cleaning, compared to the conventional cleaning method of using chemicals.

Problems caused by various membranes used in RO include concentration polarization, membrane deterioration, scaling and fouling. Some substances are often accumulated in front of the membrane during the desalination process, leaving highest concentrations directly at the membrane surface. Higher salt flux causes increased salt concentrations accumulated at the membrane surface. Therefore, the salt rejection decreases. This is called concentration polarization. A higher concentration of salt at the feed side of the membrane surface increases osmotic pressure, reducing the water flux[11].

Membrane deterioration could be caused by chemicals used in pre-treatment of the reverse osmosis. Those are often the oxidants, which may oxidize the membrane surface and damage the active membrane layer with an even trace amount[8].

Scaling is a situation in which inorganic compounds are super-saturated on the feed side. By flushing membrane with acid, we can remove scaling for some compounds. But as it (namely spiral wound modules) is often impossible to completely remove the crystalline mud out of the module, pre-treatment is crucial for stabilization of substances[8].

Moreover, fouling can be caused by the transport of colloidal matter or by biological growth, the so-called biofouling. The fouling layer increases the overall resistance to mass transfer of the membrane. Currently, to prevent fouling, we use mechanical pre-treatment of the RO feed water with screens, sand filtration and cartridge filters, and membrane treatment. For biological fouling, chlorination in pre-treatment is required. However, fouling can never fully be prevented even with pre-treatment. Therefore, we must clean membrane periodically[8].

2.2 ENVIRONMENTAL IMPACT OF RO

2.2.1 Air emissions

Desalination plants inevitably consume energy, which is produced through the process that emits greenhouse gases into the atmosphere. However, reverse osmosis requires 5–6 times less greenhouse gases than thermal processes due to an efficient energy recovery system built inside the desalination system[12].

2.2.2 Water quality and marine life

Through the desalination process, brine(saltwater) is produced. The density of brine is higher than that of seawater, causing the brine to sink towards the seabed where it influences the marine biota. Marine organisms are exposed to the high salinity water, suffering from high osmotic stress since more ions are dissolved in the water than within their body liquids[8].

Acidic or basic chemicals used in pre-treatment or membrane-washing step can also detrimentally affect the environment. To reduce this repercussion, the pre-treatment should be changed from conventional methods such as chlorination to modern methods such as UV radiation[8].

Also, in the process of water abstraction for the desalination, fish and other types of biota may be impinged by the desalination screen. Fishes collide with the screen may undergo a severe physical damage and mental stress which will ultimately lead to a high mortality rate of the fish[8].

2.2.3 Waste disposal and land emissions

At the end of almost every desalination process, waste disposal is required. Including reverse osmosis plants, disposal options of the desalination plants are often space and cost intensive. Nearly all the disposal options may further cause a certain environmental impact such as groundwater contamination.

Also, throughout several options, the rejected brine solution from the plant may increase the salinity of the groundwater source, impacting the plant growth and soil fertility[13]. As such, saltier groundwater may negatively impact the subsequent desalination process as it will provide a highly saline feed water to the plant, forming a positive feedback loop.

2.3 ENERGY CONSUMPTION AND COST

2.3.1 Energy consumption

The whole part of the RO plant - the intake, pumping, pretreatment system and most importantly pressure applying system for the RO system – demands huge amount of energy. In the late 1970s, old sea water reverse osmosis plants consumed almost 20 kWh/m^3 of energy. However, due to the development on more efficient membranes, new membrane materials, and the use of energy recovery devices, energy consumption was significantly reduced to about 3.5 kWh/m^3 by the end of the 1990s[14] (Fig. 4). This huge reduction in the energy consumption enabled the RO system to be the best viable option for desalination plant.

2.3.2 Cost

The cost of RO desalination has steadily decreased from the 1970s. An abrupt development in membrane materials, pumping mechanism, and energy recovery systems have led to desalination costs as low as 0.53 $\$/m^3$[15].

However, due to ever-increasing construction and energy costs further, price increase is expected[8]. Therefore, there is an urgent need to develop future technologies in the direction of reducing both energy consumption and cost by maximizing the merits: converging RO with other technologies as well as increasing the efficiency of the RO membrane.

2.4 FUTURE DEVELOPMENT

A high flux membrane with a better energy recovery system or a combination with ion-selective nanofiltration membranes could make a development in the reverse osmosis plant. Nanofiltration may not only aid the pre-treatment of RO feed water by reducing scaling potential, but also show higher system recovery and reduction in chemicals demand. Thus, pre-treatment of the solution with NF membranes could significantly increase the flux, decreasing energy consumption and overall cost of reverse osmosis.

Some scientists proposed that the hybridized NF–RO low cost seawater desalination process showed that, at the low pressure of only 22 bar, the Ca^{2+}, Ca^{2+} Ca^{2+}, Ca^{2+} and total hardness rejection of NF were 89.4%, 94.0%, 97.8%, 96.6% and 93.3%, respectively, and the rejection rate of monovalent ions (Ca^{2+}, Ca^{2+}) was 40.3%, achieving about 27% reduction in the net water production cost from one-stage SWRO[16-18]. So the future research related to NF-RO systems should be continued.

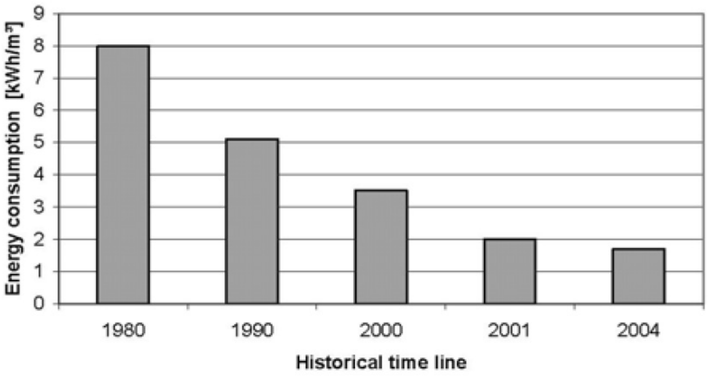

Fig. 4 Development of achievable energy consumption in RO desalination processes[14]

3. MEMBRANE DISTILLATION (MD)

Membrane distillation may allow us to undergo the desalination process with certain advantages such as compactness, low energy consumption, and the ability to use a low temperature. Also, the membrane distillation desalination plant may exhibit immunity to fouling[19].

As the vapor pressure of the concentrated solution increases than that of the cold fluid, water starts to evaporate at the hot side of the membrane. The vapor permeates through the membrane pores, which is then condensed by the cold fluid right after. The increase in vapor pressure occurs due to the temperature difference between the hot and cold faces of the membrane[19].

The process did not gain attention as an option for the desalination process although it was introduced in the late 1960s[20]. This was due to the fact that there wasn't any membrane that can be used for the desalination process at a reasonable price[19].

There are four configurations by which that MD desalination process can be classified. These are Direct Contact Membrane Distillation (DCMD), Vacuum Membrane Distillation (VMD), Air Gap Membrane Distillation (AGMD), Sweeping gas Membrane Distillation (SGMD).

As AGMD and DCMD processes do not need a condenser, they can be best utilized in the circumstances in which water is a permeating flux. On the other hand, two other methods, SGMD and VMD, are usually utilized to remove volatile organic or dissolved gas from an aqueous solution[19].

MD fluxes are not very sensitive to salinity. However, fluxes are hugely affected by the feed solution temperature. Permeate flux increases as the temperature increases because the vapor pressure is more than directly proportional to the temperature[19].

Moreover, MD process features a high selectivity: the water produced by the process is regarded as completely pure water.

The size of the MD systems can be very compact. To be specific, the height of the MSF stage is usually in the range of 4--6 m whereas the height of the MD cell is within 1 cm. This avoids the space-intensive nature of MSF plants.

3.1 ABOUT MEMBRANE

The characteristics for an optimum membrane for the membrane distillation may include next five aspects: a negligible permeability to the liquids, high porosity for the vapor phase, high resistance to heat flow by conduction, a sufficient but not excessive thickness, and low moisture adsorptivity[21]. Last but not least, the longevity of the membrane's usage is also one of the desirable quality of an ideal membrane[19].

It can be assumed that there won't be a severe fouling occurrence in MD plant due to its large pore advantage, but in effect it's obvious that fouling exists and affects the effectiveness and the life of the membrane according to several experimental studies. However, in case of biofouling, the membrane distillation process showed resistance toward it. Still, as the fouling problems exist, like the other desalination processes, pretreatment has a crucial, positive influence on this process[22, 23].

Furthermore, the membrane of MD plants can be fabricated with almost any chemically resistant polymers that exhibit highly hydrophobic properties. This is because the membrane does not react electrochemically with the solution. The chemicals added to the surface of the membrane may thus enhance the longevity of the membrane.

3.2 ENVIRONMENTAL IMPACT OF MD

Because MD is much less sensitive to the concentration of feed solution, MD can use a rejected brine from RO as the feed solution; from this process, freshwater can be produced, which reduces environmentally harmful residues of RO at the same time. Therefore, the membrane distillation can have an indirect positive impact on the environment by reducing the amount of left brine solution of RO, which can disturb the marine environment by increasing the salinity of the environment. This advantage indicates that the combined desalination plant with reverse osmosis and membrane

distillation technology may produce more than twice as much water as a single plant at the same cost[19].

3.3 ENERGY CONSUMPTION AND COST

As the process includes the distillation process, the energy demand will be high. But this can be compensated by utilizing low-grade waste energy, heat recovery system, and integration with other membrane processes. Due to its less sensitivity to the concentration, the plant may maintain its performance roughly the same for high concentration feedwaters with a similar energy demand. The cost of the plant may be like that of the RO on a similar production scale.

3.4 FUTURE DEVELOPMENT

As expressed above, MD has the advantage of compactness, low energy consumption, and immunity to fouling. So, there can be a projection that the MD plant will become a more viable and popular method for desalination.

Since this technique involves a distillation step, the membrane would have been developed to deal with a gas form. However, when the temperature drops, all gases are liquified. Therefore, there would be a significant effect on the membrane. So further research on this area is needed to extend the duration of the membrane.

4. FORWARD OSMOSIS

Forward osmosis is a technique using natural phenomenon of osmosis: water goes to solution which has higher concentration. Like reverse osmosis, it needs membrane in the system. This technology is often used for the hybrid FO-RO system. In this FO–RO system, the role of FO pass was drawing water from seawater, and the RO produced freshwater by concentrating the diluted FO draw solution.

4.1 ABOUT MEMBRANE

A membrane commercially the most used for forward osmosis plants is a membrane made of cellulose triacetate. This membrane has a shortcoming of being easily degraded by the exposure to an ammonium bicarbonate solution[24]. Moreover, the membrane performs poor salt rejection and water permeability. Thus, the membrane is not appropriate for a desalination plant.

The thin-film-composite membrane is usually designed for RO usage. As forward osmosis desalination is not a pressure-driven process, TFC membrane thus is not suitable for forward osmosis[25]. Also, the concentration polarization may be a critical factor that will make the performance of TFC in FO poorer. But, the recently modified version of the TFC membrane may provide a better solution for the FO process. The key point for this modification is making the supporting polysulfone (PSF) membrane very thin. In addition, the membrane should also ensure high water flux. To this end, often the file is immersed into the water bath. As a result, the finger-like pore is formed, which reduces the water flux resistance[26].

4.2 ENVIRONMENTAL IMPACT

Under the high osmotic pressure, forward osmosis plant exhibits a high-water reclamation, which is ultimately helpful for diminishing the amount of rejected brines. Also, the forward osmosis membranes can be cleaned by physical cleaning and osmotic backwash. Unlike others, this characteristic makes it possible for FO plant not to use chemicals for their membrane cleaning. Absence of chemicals will reduce the negative ecological effect[27].

4.3 ENERGY CONSUMPTION AND COST

There is a perception that forward osmosis will require less amount of energy because it is not a pressure driven process. But, contrast to the general assumption, the forward osmosis plant actually has a high energy demand during the desalination of the seawater. Also, there is an additional step for regenerating the draw solution within the forward osmosis process, which additionally consumes energy. There are consistent developments on the draw solution and membrane development to lower the energy consumption of the FO plant. FO plant can be used in other desalination processes such as RO. In the RO plant, it can dilute the solution easily for RO plant, lowering the energy consumption[19].

4.4 FUTURE DEVELOPMENT

Recently, several pieces of research have reported that adding certain polymers to the membrane will ensure the hydrophilic nature of the membrane. Interfacial polymerization of membranes with these polymers will allow the membrane to perform better as the hydrophilic nature of the polymer will draw a greater water flux.

5. NANOFILTRATION (NF)

Nanofiltration technology allows faster transportation than classical reverse osmosis. It can also operate under lower operation pressures, higher water fluxes, lower investment, and with high rejection rates for scale formation bivalent ions, especially anions[28]. Especially, the usage of graphene membrane allows the membrane to have a negligible thickness and high mechanical strength[29], which cannot be featured by conventional RO membranes.

Nowadays, nanofiltration is used as the pre-treatment in combination with other technologies such as RO and FO, rather than technology itself. This is because the introduction of NF technology into the membrane has the advantage of reducing the energy and cost involved in pre-treatment during the desalination process.

Also, it enhances the efficiency of a desalination process: minimized hardness, microorganisms and turbidity helped the scientists to reduce the amount of chemicals used. Also, it lowers the energy consumption and water production cost, thus leading to more environmentally friendly practices[30]. As the efficiency of desalination itself increases when high-qualified and high-efficiency pre-treatment are performed, the society's interest in nanofiltration technology is increasing. Therefore, in addition to its own characteristics of NF, features of the plant in a form of fusion with other technologies - such as RO and FO - are presented below.

5.1 ABOUT MEMBRANE

5.1.1 Pore Chemistry

Nanopores may be beneficial for the graphene membrane. Nanopores can be introduced into graphene's structure through passivating chemical functional groups to the unsaturated carbon atoms[31]. There have been recent studies and developments on the methods for introducing a nanopore into the graphene membrane. Amongst various pore structures, there are namely two types of pore chemistry: hydrogenated pores and hydroxylated pores. Hydrogenated pores are obtained by passivating each carbon with a hydrogen atom while hydroxylated pores are gained through passivating carbon atoms with H- and OH-groups. (Fig. 5)

Hydrogenated pores exhibit a higher level of order. This feature of hydrogenated pores is due to the fact that the hydrogen passivation is hydrophobic, which reduces the possibility of formation of hydrogen bonding to water molecules. In contrast, hydroxylated pores can freely form a hydrogen bond with water molecules, enabling a smoother entropic landscape for traversing of water molecules[31]. Hence, hydroxylate pores exhibit a higher water flux and permeability, which is crucial for the water desalination.

However, due to its functional group, hydroxylated pores can experience a lower salt rejection. Similar to the water flux, OH functional group in the hydroxylated pores can form a hydrogen bond with salt ions, causing a better entropic landscape for ionic passage. As there is a lower free energy free barrier, for a given pressure and pore size, the salt rejection may be lower for hydroxylated pores.

5.1.2 Pore Size

As the pore size decreases, the size of the passage increases and therefore the salt rejection rate naturally increases. But the salt rejection performance is inversely proportional to the pressure[31].

5.3 IMPROVEMENTS WHEN INTEGRATED WITH RO

When NF is used as a pre-treatment for RO, the ion content could be reduced to 220 ppm. Also, the water recovery was increased from 28% to 56% while the power consumption was reduced from 9.596 kWh/m3 to 5.858 kWh/m3[32]. sThe RO–NF desalination process can further increase the overall water recovery. In the process, the concentrated water produced by the RO process was further desalted by NF process, where the permeate water was fed back to RO plant. The cost was 0.57 $/m3, 20.06% lower than single stage RO process[33]. Compared with the two stage RO process, RO–NF process saved more investment costs and electric energy.

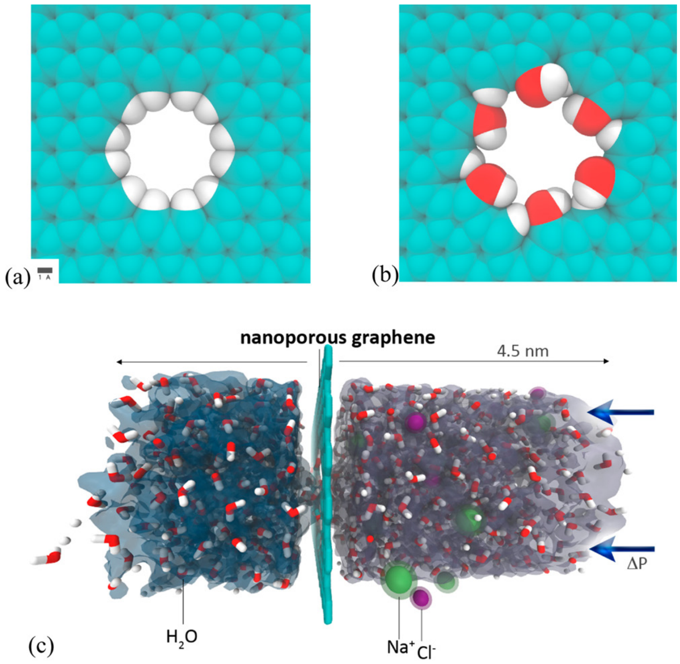

Fig. 5 Hydrogenated (a) and hydroxylated (b) graphene pores, and (c) side view of the computational system investigated in this work.

5.4 IMPROVEMENTS WHEN INTEGRATED WITH FO

FO and NF are integrated as a form of 'FO–NF–NF' system. Water is first driven from seawater to draw solution through the FO membrane, and then the two-stage NF process removes salt from diluted draw solution to form fresh water. The rejection percentage of FO membrane for ions such as Ca^{2+} and $Ca^{2+}$are close to 100%[34].

5.5 FUTURE DEVELOPMENT

Fusing NF with other technologies would lower the costs of desalination systems. Especially the dual stage NF seawater desalination process using high rejection NF membrane is a promising technology for improving water quality and lowering energy consumption.

Including NF steps may increase the complexity and cost of desalination plant. Therefore, the cost, permeate quality, environmental impact and special requirements of the NF membranes are critical for any successful cost reduction. High cut-off NF membrane with high flux and better antifouling properties should be further investigated and developed for lower cost desalination applications[35].

6. CONCLUSION

Nowadays, membrane desalination plants are under the limelight as the plants are ensuring the creation of fresh usable water for the industrial and domestic usages. Thanks to the development of the technology, there are also various types of membrane desalination plants: reverse osmosis plant, forward osmosis plant, membrane distillation plant, and nanofiltration plant. Due to the different working mechanisms, each plant has distinct advantages and disadvantages. To be specific, some features high-cost saving whereas others exhibit reduced environmental impacts.

The paper delves into these different characteristics of each desalination plant. In terms of energy consumption and cost, it is shown that the reverse osmosis plant allows low energy consumption due to its recently developed pumps. Also, the integrated plant with reverse and forwards osmosis has a promising future due to its increased energy savings with the ability of forward osmosis membrane to dilute the feed solution for the reverse osmosis plant. Forward osmosis desalination also had less negative environmental impacts. Unlike other plants, the forward osmosis plant requires fewer chemical additives since it is easy to prevent membrane fouling by the membrane backwash and physical cleaning. Also, its nature of high-water reclamation under high osmotic pressure enables the forward osmosis to lower the amount of rejected brine solution, which disturbs the marine environment by increasing the salinity. Furthermore, membrane distillation was also a highly eco-friendly process as it can handle the rejected brine solution as its performance is less dependent on the feed solution concentration.

As such, some plants, such as reverse osmosis, have an advantage in energy consumption while having a weak point in environmental impact when it works alone. Therefore, it is hard to say which plant is the best: each plant needs some development. In fact, the hybrid plants such as reverse osmosis & nanofiltration plants or reverse osmosis & forward osmosis plants may make up for the disadvantage of each other. Hence, the development of these hybrid plants should be focused. Because of the imminent environmental issues nowadays, the future development on the hybrid system should place the impacts of the plant on the surroundings for the first priority.

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