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Membrane processes and their potential applications for fresh water provision in Vietnam

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Abstract

Water treatment using membrane processes can be a pragmatic approach to mitigate the current fresh water scarcity in Vietnam. This paper provides a comprehensive review of mature and emerging membrane processes destined for water treatment. These processes include pressure-driven filtration (e.g. microfiltration, ultrafiltration, nanofiltration, and reverse osmosis), osmotically driven forward osmosis, and thermally driven membrane distillation. Fundamentals of the membrane processes were firstly provided. Additionally, the influences of membrane properties, module configurations, and operating conditions on fresh water production rate, membrane fouling propensity, and energy consumption of the membrane processes were analyzed. Finally, potential applications of the membrane processes to alleviate the fresh water scarcity in Vietnam were discussed.

Keywords. membrane processes, wastewater treatment, wastewater reclamation, desalination, fresh water scarcity.

1. INTRODUCTION

In recent years, Vietnam has been confronted with increasingly serious fresh water scarcity. Even though Vietnam has 2360 rivers, only about 40 % of the country population has access to fresh water owning to limited infrastructure and financial capacity [1]. The remaining population, which is mostly in rural areas, relies heavily on groundwater for drinking water and sanitation. There have been evidences that drinking water sourced from groundwater contaminated with various toxins (i.e. most notably arsenic) can result in chronic health issues such as cancer, neurological and skin problems [2]. In addition, because more than 65 % of fresh water resource originates from catchments outside Vietnam, the fresh water scarcity has been seriously aggravated by activities external to the country [1]. Reoccurring droughts and seawater intrusion in the Mekong Delta have demonstrated the susceptibility of Vietnam fresh water resource to external factors.

Water treatment plays a vital role in mitigating the current fresh water scarcity in Vietnam. Water treatment processes improve the quality of fresh water to meet the drinking water standards. Wastewater treatment processes help to remove contaminants from municipal or industrial waste streams before returning the treated waters to the environment, thus alleviating the pollution of fresh water sources. On the other hand, desalination processes remove dissolved salts and other contaminants from seawater or brackish water to produce fresh water. It is worth mentioning that Vietnam has a long coastal line, thousands of islands, and a large portion of its population inhabiting in coastal areas. Thus, desalination might be a feasible approach to augmenting fresh water availability in Vietnam and reducing the reliance of the country to fresh water sources that originate outside the country.

Membrane processes have been widely used for water treatment in many countries around the world. Amongst a great deal of membrane processes, pressure-driven membrane filtration including microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO) have found commercial applications for drinking water production, wastewater reclamation and recycling, and seawater and brackish water desalination. Compared to conventional water treatment methods, the pressure-driven membrane filtration offers several important attributes such as process modularization and compactness, reliable separation functionality, and full automation with minimal chemical use. However, intensive energy consumption and high risk of membrane fouling are the major drawbacks of the pressure-driven membrane processes. Emerging membrane processes such as membrane distillation (MD) and forward osmosis (FO) have demonstrated great promise for water treatment applications with respects to energy cost and membrane fouling propensity.

This paper aims at providing a comprehensive review of membrane processes for water treatment applications. The review starts with providing fundamental knowledge of the membrane processes including mature pressure-driven MF, UF, NF, and RO as well as the emerging MD and FO processes. Factors influencing the separation efficiency, fresh water production rate, energy consumption, and membrane fouling propensity of these processes are analyzed. The potential applications of these membrane processes for fresh water provision in Vietnam are also critically discussed.

2. MEMBRANE PROCESSES

2.1. Pressure-driven membrane processes

Pressure-driven membrane processes are classified regarding membrane pore sizes, working pressure, and hence their applications (Fig. 1). Amongst these processes, MF and UF utilize porous membranes with pore sizes respectively in the range of 0.05-10 μm and 5-100 nm. Correspondingly, MF is destined for removal of suspended particles and large colloids, whereas UF can be used to remove macromolecules, pathogens, and proteins (Fig. 1). Examples of MF and UF applications for water treatment include separation of oil/water emulsions [3], separation of bacteria from water in biological wastewater treatment [4], and pre-treatment of feed water prior to other separation processes such as NF and RO [5-7].

Water flux through the membrane in MF/UF can be described by Darcy's law [8]:

$$J = A \cdot \Delta P \tag{1}$$

where J is expressed in L/(m^2·h); A is the permeability constant, which is a function of the fluid dynamic viscosity and membrane structural factors such as membrane porosity, pore size distribution, pore tortuosity, and membrane thickness; and ΔP is the applied transmembrane pressure (TMP). It is noteworthy that the linear relationship between water flux and ΔP in Eq. (1) only exists in a certain TMP range depending on characteristics of feed waters. When ΔP exceeds a certain value, increase in ΔP has no effect on water flux of the MF/UF process. This is because of the accumulation of retained solutes that leads to the formation of a cake layer on the MF/UF membrane surface (i.e. membrane fouling) [9].

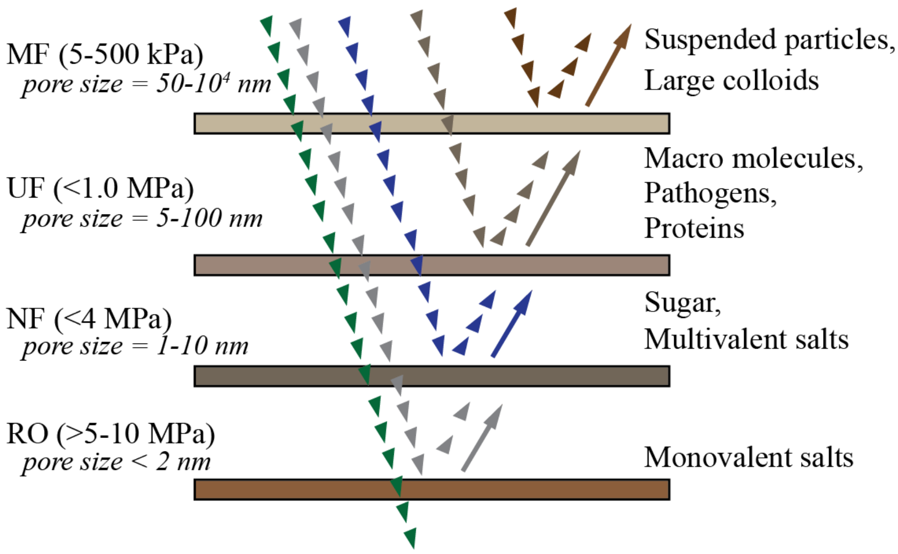

Figure 1: The ranges of pore sizes, applied pressure, and applications of pressure-driven membrane processes

Depending on fouling propensity of the feed water, the MF/UF process can be operated in dead-end or cross-flow modes (Fig. 2). In a dead-end operation, the feed water flows perpendicularly to the membrane surface, and all water permeates through the membrane while particles larger than membrane pore sizes are retained on the membrane surface. On the other hand, in cross-flow operation, the feed water flows along the membrane, thus only a portion of retained particles accumulates on the membrane surface. The dead-end operation is more energy efficient but also much more prone to membrane fouling than the cross-flow operation. Therefore, dead-end mode is often applied for feed waters that pose a low risk of membrane fouling (i.e. pre-treatment in wastewater recycling and seawater desalination), whereas cross-flow operation is practiced in applications to treat feed waters with high contents of organic matters, colloidal components, and suspended solids [8].

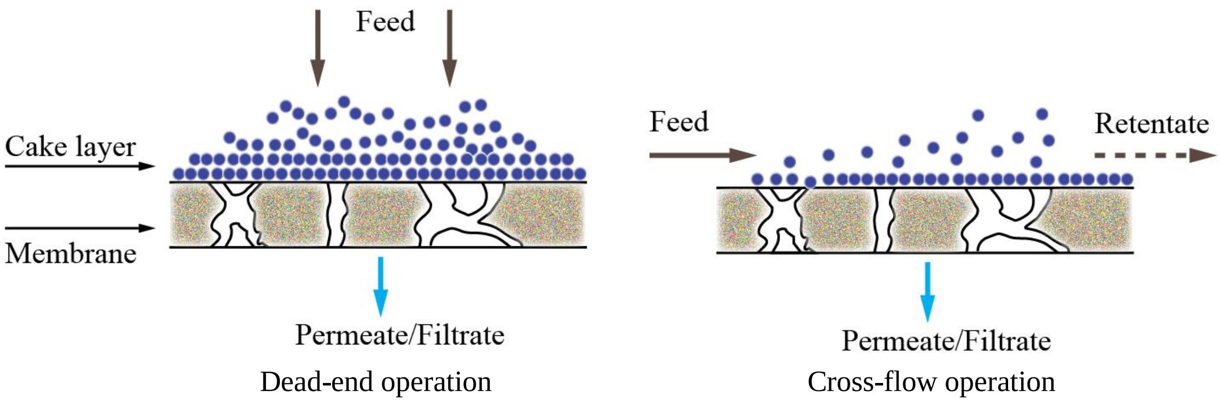

Figure 2: Dead-end and cross-flow operation modes during the MF/UF separation process

Membrane fouling is generally an intrinsic problem for many membrane separation processes. However, it can be effectively prevented by process optimization in MF/UF. There is a critical water flux, below which no fouling occurs and a stable MF/UF water flux can be obtained at a constant TMP [9, 10]. Operating the MF/UF process above the critical flux ultimately leads to membrane fouling. However, unlike in NF and RO, fouling layers on the MF/UF membrane can be completely removed by membrane backwashing, sonication, and chemical cleaning; therefore, the performance of the fouled MF/UF membrane can be totally restored [11, 12].

Unlike MF/UF, RO uses a dense, semi-permeable membrane to achieve the process separation efficiency. The RO membrane is highly permeable to water but rejects almost all suspended solids and dissolved substances [13, 14]. Under the natural osmosis process, water from the permeate migrates through the membrane to the feed, hence leading to the dilution of the feed (Fig. 3). When a

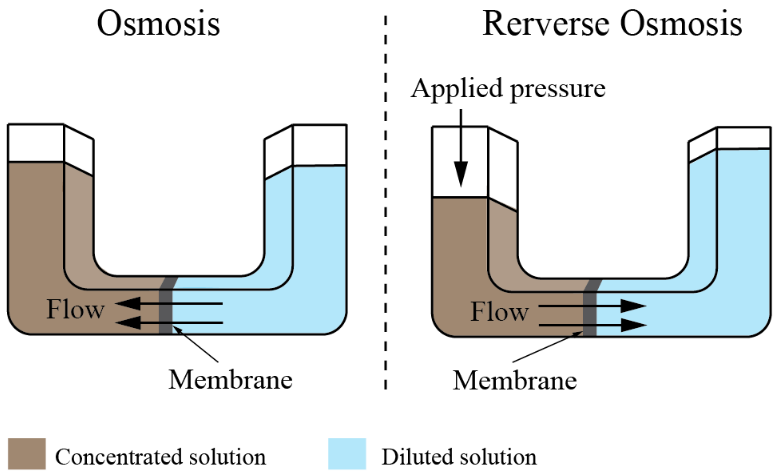

Figure 3: Principles of osmosis and reverse osmosis process

high hydraulic pressure is applied on the feed side, water is forced to reversely cross the membrane. The feed stream becomes more concentrated and fresh water is collected on the permeate side of the RO membrane. The driving force for RO separation is the hydraulic pressure difference between two sides of the membrane. This pressure difference is subjected to the osmotic pressure (i.e. the salinity) of the feed solution. Therefore, RO operating pressure strongly depends on the salinity of the feed. For seawater desalination, RO requires a hydraulic pressure ranging from 55 to 68 bar [13], whereas a lower hydraulic pressure is used to treat secondary effluent from a conventional wastewater treatment in wastewater recycling plants. Compared to conventional thermal distillation processes (e.g. multi-stage flash, multi-effect distillation, and vapor compression), RO offers a significantly lower specific energy consumption [13, 15, 16]. As a result, most of newly installed desalination and wastewater recycling plants worldwide employ RO as an integral treatment process [14].

To obtain efficient separation efficiency, RO membranes are desired to exhibit high water flux and high salt rejection. High water flux can be achieved using very thin membranes, However, reducing membrane thickness also compromises the mechanical stability of the membrane. Thus, RO membranes are mostly composed of a thin active layer and a supporting layer [13]. Commercial RO processes employ cellulose acetate (CA) and thin film composite (TFC) membranes. CA membranes were first produced for RO in the 1960s, and they are still commercially available [13]. The major drawback of CA membranes is their susceptibility to pH of the feed solution – membrane lifetime can be significantly reduced when operating CA membranes at pH below 4 or above 8. TFC membranes consist of a thin polyamide active layer and a polysulphone supporting layer. Compared to CA membranes, TFC membranes are more chemically and physically stable, demonstrating a stronger resistance to bacterial degradation and feed pH. Nevertheless, TFC membranes are very sensitive, and thus can be easily damaged by a small amount of free chlorine in the feed solution [13].

One major technical challenge to RO water treatment applications is membrane fouling [17]. Membrane fouling leads to decline in water flux and salt rejection, increase in energy consumption, and shortened membrane lifetime, thus increasing operational costs [13, 17]. To mitigate membrane fouling in RO processes, feed water pre-treatment, including pH adjustment, flocculation and filtration, anti-scalant addition, is typically required. In addition, water recovery ratios of RO processes are often restricted to prevent the precipitation of sparingly soluble salts. Despite intensive pre-treatment and limited water recoveries, membrane fouling can not be totally avoided. Chemical cleaning is required to remove fouling layers from the fouled membrane and recover its performance [13]. Unlike in MF, backwash is not allowed for the fouled RO membrane due to the risk of damage to its thin active layer. A novel RO membrane cleaning method is direct osmotic cleaning, in which a concentrated NaCl solution is shortly injected into the feed channel, inducing direct osmotic water flux from the permeate to the feed side, thus removing fouling layers from the membrane surface [18].

Nanofiltration (NF) is one pressure-driven membrane process that has applications between RO and UF. NF membranes have pore sizes typically of 1-10 nm (i.e. corresponding to molecular cut-off in the range of 300-500 Da) [19, 20]. Given these pore sizes, NF membranes offer great removal capacities of various contaminants such as bacteria, virus, pesticide, disinfection by-products, and multivalent salts from feed waters (Fig. 1). Compared to RO, NF membranes possess a longer lifetime, and NF processes can be operated at lower hydraulic pressures and obtain higher water flux, thus resulting in significant reduction in process operational and maintenance costs [19, 20]. With these notable advantages, NF has been widely applied for treatment of ground water, surface water, and wastewater as well as for pre-treatment of brackish and seawater desalination processes using RO or conventional thermal distillation [19, 20]. Recently, NF has also been extensively used for purification of pharmaceutical ingredients and for enrichment and recovery of organic solvents in biotechnological processes.

2.2. Osmotically driven forward osmosis (FO)

FO is an emerging membrane separation technology that utilizes the physical phenomenon of osmosis to transport water across a semi-permeable membrane [21, 22]. The process is driven by the difference in osmotic pressure between a dilute feed solution and a concentrated draw solution, resulting in the movement of water from the feed to the draw solution. Unlike RO where hydraulic pressure is required to overcome the feed solution osmotic pressure, FO exploits the high osmotic pressure of the draw solution, enabling the process to operate with minimal external energy input. In addition, FO membranes are highly selective, and therefore have a high rejection of a wide range of contaminants.

Most importantly, FO is capable of directly filtering feed solutions with high levels of particulate matter, and with a potentially lower fouling propensity compared to pressure-driven membrane processes. For these reasons, FO has significant promise in reclaiming water from impaired sources, including seawater desalination, wastewater treatment, and emergency drinking water production [21, 22].

Although FO has demonstrated significant promise in water reclamation applications, several major technical challenges require addressing prior to the full-scale commercialization of FO technologies. These challenges include limited water flux, high energy consumption of draw solute regeneration processes, and membrane fouling [21-23].

The achievable water flux in the FO process is primarily dependent on the type and concentration of the draw solution. Simple inorganic salts (i.e. NaCl) are the most appropriate draw solution as these salts provide a high osmotic pressure and have a low cost [23, 24]. Furthermore, simple inorganic salts are not significantly affected by internal concentration polarization (ICP), an inevitable phenomenon of the FO process. ICP occurs within the porous support layer of the membrane and relates to the difference in draw solute concentrations on the boundaries of the support layer. Therefore, draw solutes such as simple inorganic salts that are small and highly mobile are preferred [23, 24]. The cost of draw solutes is an important consideration as some of the draw solute leaks into the feed solution, also known as reverse solute flux. Reverse solute flux is influenced by the membrane characteristics, as well as the physiochemical properties of the draw solution. The lost draw solute must be replenished to maintain the osmotic pressure, and therefore is a prominent operational consideration for the FO process [23, 24].

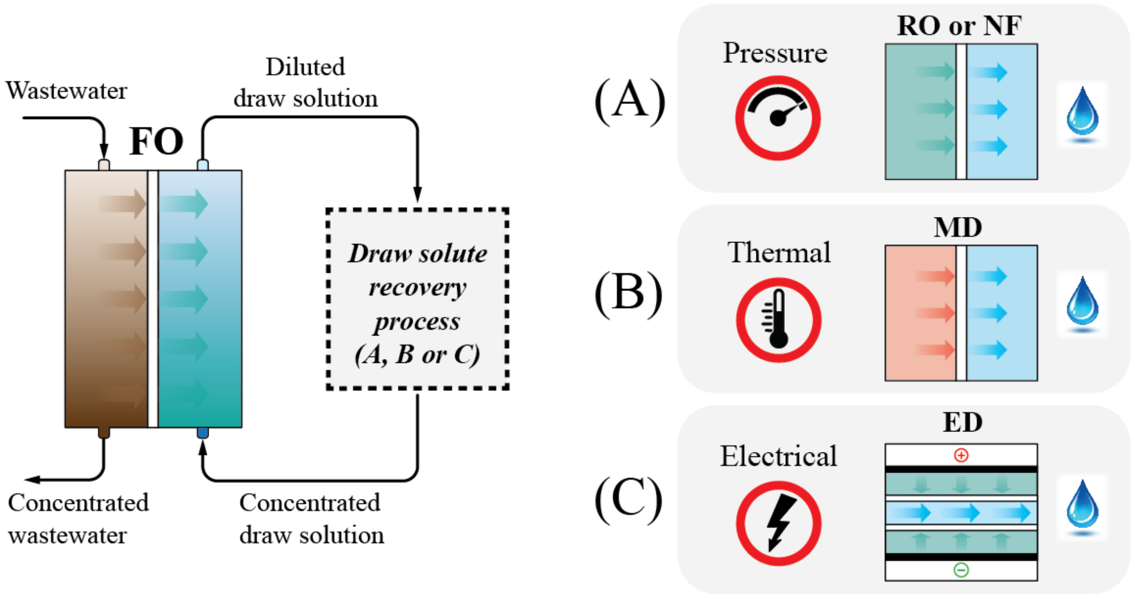

Figure 4: A schematic diagram of an FO process with various draw solution regeneration methods

The FO process can only provide pre-treatment for impaired water. To produce fresh water, it is necessary to couple FO with a draw solute regeneration process. Various desalination processes such as RO, NF, MD, or electrodialysis (ED) have been combined with FO for fresh water extraction and draw solute regeneration (Fig. 4). The draw solute regeneration process significantly influences the energy consumption of hybrid FO processes. Nonetheless, the FO process can essentially produce a foulant-free solution for, and thus improve the efficiency of the draw solute regeneration process. Amongst the hybrid processes, FO-MD systems hold significant advantages as the heat required for MD could be utilized from low-grade waste heat or solar thermal sources. Alternatively, readily available or directly usable draw solutes such as seawater, brine from other desalination process, or fertilizers have recently been explored to avoid the high energy consumption of draw solute recovery processes [25, 26].

FO is widely recognized as having a lower fouling propensity compared to pressure driven membranes due to the differences in the driving force. In RO, the high hydraulic pressure required to generate high water flux creates a compacted fouling layer that cannot be easily removed by hydraulic means. Whereas in FO, even at an identical permeate flux, the nature of the osmotic driving force creates a less dense fouling layer and therefore

FO fouling is mostly reversible. Nevertheless, membrane fouling remains a prominent issue for FO development, particularly when treating complex wastewater solutions. Several factors strongly influence FO membrane fouling, including foulant characteristics, membrane properties, and process conditions. There is a consensus amongst researchers that FO fouling can be successfully controlled by optimizing the feed hydrodynamic conditions without the need for chemical cleaning [26]. However, improved hydrodynamic conditions inevitably relate to an increased energy consumption of the FO process.

2.3. Thermally driven membrane distillation (MD)

MD is a combination of thermal distillation and membrane separation. In MD, a microporous hydrophobic membrane is used as a barrier to prevent the permeation of liquid water while allowing the transfer of water vapor through the membrane pores [27]. As a result, salts and other nonvolatile contaminants are retained on the feed side, and fresh water is obtained on the permeate side of the membrane. The driving force of MD is the water vapor pressure difference induced by a temperature gradient across the membrane. Thus, MD water flux is not significantly affected by the osmotic pressure of the feed solution as compared to RO, and hence MD is capable of treating highly saline solutions, including brines from other desalination processes [28-30]. More importantly, MD systems can be manufactured from inexpensive plastic materials due to the absence of high hydraulic pressure, resulting in a significant saving in MD capital costs. Finally, MD is operated at feed temperature ranging from 40 to 80 °C. Consequently, low-grade waste heat or solar thermal can be utilized as the primary source of energy in MD processes.

MD can be operated in four basic configurations, including direct contact membrane distillation (DCMD), air gap membrane distillation (AGMD), vacuum membrane distillation (VMD), and sweeping gas membrane distillation (SGMD) (Fig. 5). Amongst these configurations, DCMD has the simplest arrangement and is the most widely used in MD studies. However, DCMD demonstrates the lowest thermal efficiency compared to other configurations owning to its noticeable conduction heat loss from the feed to the permeate through the membrane. The introduction of vacuum and sweeping gas on the permeate side of the membrane helps reduce the conduction heat loss, thus improving thermal efficiency of VMD and SGMD. It is noteworthy that VMD and SGMD require an external condenser to converse vapor into liquid, hence rendering these configurations more complex than DCMD. In AGMD, an air gap is inserted between the feed and permeate streams, alleviating the conduction heat loss and at the same time facilitating the recovery of the latent heat of condensation to preheat the feed. Therefore, AGMD exhibits lower process complexity than VMD and SGMD, and a higher thermal efficiency than DCMD. Given these attributes, AGMD has been the most used configuration for pilot and small-scale seawater desalination applications.

Most of MD systems utilize hydrophobic membranes that are originally designed for MF with pore sizes in the range of 0.1 to 0.5 μm, thickness from 60 to 180 μm, and porosity below 80% [31]. The membrane pore size governs the mass transfer mechanism, and thus the water flux of MD; larger pore sizes produce more flux. However, increasing pore sizes also involves the risk of membrane pore wetting according to the Laplace equation [31, 32]. Thus, optimum pore size should be determined for MD applications. The membrane thickness is also an important characteristic of MD membranes. Thicker membrane helps reduce the heat loss via conduction, resulting in an improved thermal efficiency of MD processes. However, thick membranes exhibit more resistance to the transfer of water vapor, thus reducing water flux of MD. MD membranes having higher porosity produce more water flux as they offer more active surface areas for water evaporation. Unfortunately, increasing porosity of the membrane compromises its physical strength. Finally, membranes used in MD are expected to be as hydrophobic as possible to prevent membrane pore wetting and increase water flux.

Operating conditions, including temperatures and circulation rates of process streams, the concentration of the feed water, the thickness of air gap in AGMD, vacuum pressure in VMD, and sweeping gas flow rate in SGMD, also exert strong influences on the process water flux and the quality of permeate. Generally, increasing feed temperature, vacuum pressure, and sweeping gas circulation rate increases the driving force, thus promoting MD water flux. Increasing water and sweeping gas circulation rates also helps mitigate temperature and concentration polarization effects, which are intrinsic problems of MD, hence further raise water flux. The thickness of the air gap in AGMD strongly influences both water flux and thermal efficiency of

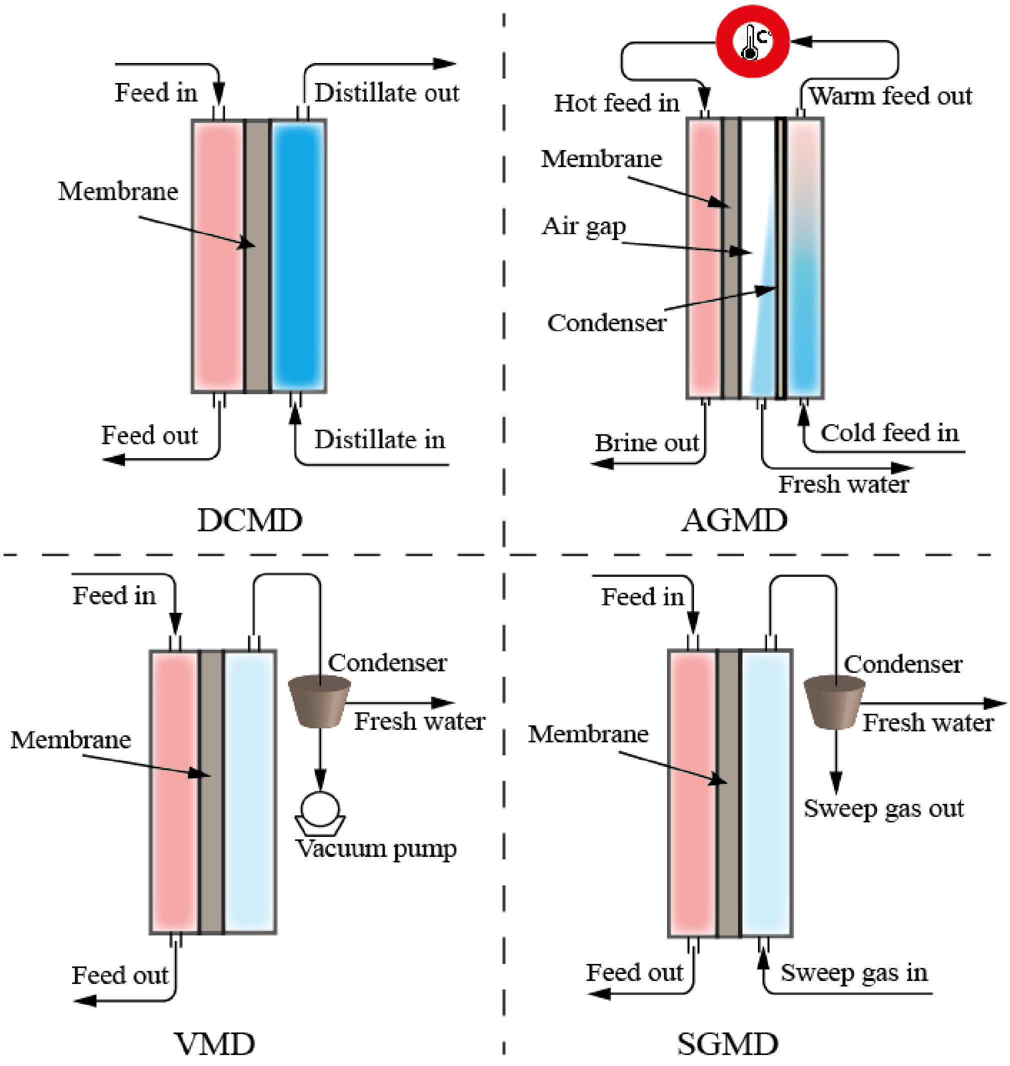

Figure 5: Four basic configurations of MD

the process. Using thicker air gap reduces the heat conduction through the membrane, therefore improving process thermal efficiency. However, thicker air gap also increases the mass transfer resistance, hence leading to lower water flux [27].

The MD process exhibits a higher specific energy consumption (i.e. the amount of energy consumed per 1 m^3 of obtained product) compared to RO. As a thermal distillation process, MD requires significant amounts of heating and cooling for phase conversion from liquid to vapor and vice versus. The latent heat of vapor condensation can be recovered to reduce specific thermal energy consumption (STEC) of the MD process. AGMD of seawater with STEC as low as 90 kWh/m^3 has been reported [33], whereas a benchmark seawater RO process has a specific energy consumption of 3-4 kWh/m^3 [15]. It is noteworthy that MD can utilize low-grade waste heat or solar thermal energy available on sites; therefore, MD is considered an energy-saving alternative to RO [28, 34].

Membrane fouling is a technical challenge to the realization of MD for desalination and wastewater treatment [35, 36]. Membrane fouling inevitably leads to a reduction in water flux and deterioration in the quality of water product. As foulants and scalants deposit on the membrane surface, they reduce the membrane active surface for water evaporation, decrease partial water vapor pressure on the membrane surface, and might partially block membrane pores. They also alter the hydrophobicity of the membrane, resulting in liquid intrusion through the membrane pores, thus compromising the separation efficiency of MD processes. MD is less susceptible to membrane fouling as compared to RO [35, 36]. However, severe fouling and scaling have been reported for MD treatment of brines [29, 37] or seawater at high water recoveries [38]. Thus, fouling mitigation techniques such as pre-filtration of feed water, antiscalant addition, membrane cleaning, and process optimization have been proposed and practiced to control membrane fouling in MD.

3. POTENTIAL APPLICATIONS OF MEMBRANE PROCESSES IN VIETNAM

3.1. Drinking water provision at house-hold level in urban areas

Pressure-driven membrane filtration can be a practical solution to drinking water provision at house-hold level in Vietnam. Most urban areas in Vietnam have access to fresh water provided by centralized water treatment plants. Water intake to these fresh water production plants is sourced mainly from surface water (70 %) and ground water (30 %) [1]. The treatment plants sourced from surface water utilize conventional treatment processes including flocculation, coagulations, sedimentation, sand-bed filtration, and subsequent chlorination for disinfection [1]. On the other hand, ground water treatment plants employ aeration for iron removal in an air blower or packed tower aerator, contact sedimentation, and filtration following by disinfection [1]. In general, the water treatment plants (i.e. sourced either from surface water or ground water) can provide fresh water of drinking water standards (i.e. QCVN 01:2009/BYT) [39]. However, fresh water delivered to end users only meets the standards for domestic water (i.e. QCVN 02:2009/BYT) [40], but is not directly drinkable. This is because of the inadequate quality of water pipe systems that leads to the contamination of the product water during its distribution from the plants to taps. Contaminants found in tap water can include arsenic (i.e. most notably), ammonium compounds, and traces of pesticides and toxic chemicals. Thus, extra treatment of tap water is required to obtain drinking water in Vietnamese households. In this context, pressure-driven membrane processes can be tapped on. Indeed, RO has proven to be able to treat ground water to produce drinking water with arsenic concentration 20 times lower than its maximum allowable level in drinking water [41]. The cost analysis of the product water also reveals that RO is an economically feasible process for arsenic-safe drinking water production [42]. It is, however, noteworthy that RO requires a reliable electrical energy source to power high-pressure pumps; therefore, it might not be an ideal process for drinking water provision in remote mountainous areas and islands in Vietnam.

3.2. Fresh water supply via desalination in remote coastal areas and islands

Currently, fresh water provision in Vietnam remote coastal areas and islands are implemented via rainwater harvesting systems or shipping fresh water from the mainland. The current methods for fresh water supply are either unreliable and seasonal-dependent or uneconomical. Both RO and MD can be employed to desalinate seawater for fresh water provision in these areas. However, seawater RO desalination is only energy-efficient and cost-competitive for large-scale operation [16], and might not be ideal for small-scale seawater desalination for remote areas and islands. Seawater RO desalination process is highly prone to membrane fouling, thus requiring extensive feed water pre-treatment together with restricted water recovery ratios (i.e. < 50 %) [43]. In addition, a high-pressure pump is used to overcome the osmotic pressure of seawater feed in RO, resulting in the demand for expensive stainless-steel components. On the other hand, MD has the ability to directly use waste heat or solar thermal energy available on site; therefore, it is arguably the most suitable desalination process to provide fresh water to small communities in remote coastal areas in Vietnam [44-46].

Several pilot and small-scale seawater MD desalination demonstrations have been conducted. Most recently, Duong et al. [33] have demonstrated a single-pass air gap membrane distillation (AGMD) process of seawater (Fig. 6) without any feed water pre-treatment. The process was operated for over 24 hours with actual seawater. Stable water flux and distillate of high quality were obtained with no signs of membrane fouling. Shim et al. [47] incorporated solar energy into a pilot-scale seawater direct contact membrane distillation (DCMD) desalination system for over three months. Solar energy could supply up to 95% of the thermal energy required by the DCMD system. Chafidz et al. [44] developed a portable, solar-driven MD desalination system for arid remote areas in Saudi Arabia. The system was described as environmentally friendly and sustainable [44].

MD has a great potential for small-scale seawater desalination application in Vietnam, which has more than 3000 km of coastline and many islands. Given their low investment and operational costs, seawater MD desalination systems can be installed to provide fresh water to people and military personnel in coastal areas or on islands, such as the Spratly Islands. Small-scale MD systems can also be built on fishing boats to utilize the waste heat from boat engines for fresh water production.

With an MD system on boats, lack of fresh water will no longer be a concern for long-traveled fishermen. The adequate fresh water provision for military personnel and fishermen is arguable of great importance for the fulfillment of the Vietnam Sea Strategy to 2020.

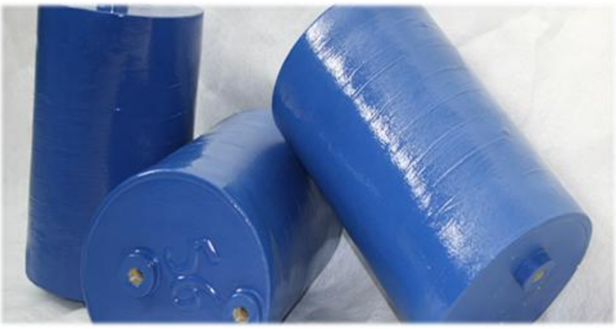

Figure 6: Photographs of pilot MD membrane modules and system

3.3. Wastewater treatment and reclamation

Treatment and reclamation of wastewater can be a practical measure for fresh water augmentation and in tandem environment protection in Vietnam [48]. Wastewater treatment can exploit conventional activated sludge (CAS) technology or membrane bioreactors (MBRs), which integrate a low-pressure membrane filtration with a conventional biological sludge process. Compared to the CAS process, MBRs demonstrate key advantages, including smaller footprint, less sludge production, and higher effluent quality [49-51]. MBRs also suffer from two major drawbacks, namely high energy consumption and the propensity of membrane fouling [49, 51].

Recently, FO and MD have been integrated into MBRs to overcome the aforementioned drawbacks [23, 49, 52]. The integration of FO with an MBR generates a new process termed osmotic membrane bioreactor (OMBR). OMBR was first proposed in 2008 and its popularity has soared recently [49]. OMBR employs an FO membrane in place of a low pressure-driven filtration process. The osmotic pressure difference between the mixed liquor and the FO draw solution is the driving force of OMBR. Given the low fouling propensity of FO, membrane fouling in OMBR can be effectively mitigated compared to that of MBRs. In addition, the energy consumption of the OMBR wastewater treatment process can possibly be lower than that of MBRs when FO draw solution regeneration is not required [49, 52, 53]. Therefore, OMBR might be an ideal technology platform for wastewater treatment and reclamation in Vietnam. Nevertheless, several key challenges, including salinity build-up, low water flux, and membrane stability, need to be addressed for further development of OMBR.

Given its ability to utilize waste heat as its main energy source, MD has been combined with the thermophilic bioprocess to create a novel wastewater treatment process called membrane distillation bioreactor (MDBR) [52, 54]. Unlike MBRs and OMBR, the driving force for water transport is induced by heating the mixed liquor (i.e. operating temperature of 45-60 °C), and water transfers through the membrane in vapor form in MDBR. Thus, MDBR can obtain permeate of much higher quality than that of MBRs, and MDBR can be an energy-saving alternative to MBRs for treatment of hot wastewater or where waste heat is readily available [52, 54].

3.4. Drinking water supply for disaster relief and special operations

NF, RO, and FO might be relied on for drinking water supply during disaster relief or special operations. Many portable compact NF/RO water filter systems with competitive prices are commercially available worldwide. These systems, however, can obtain drinking water when reliable grid electricity can be accessed to for the operation of high-pressure pumps. The heavy reliance on grid electricity possibly constrains the application of NF/RO for drinking water supply during natural disasters. On the other hand, FO utilizes the nature of an osmotic process, in which fresh water from a diluted solution will transfer to a more concentrated one. The FO process can be engineered to make an energy-free water filtration system. Indeed, a commercial product called HydroPack has been developed and offered to the global market. HydroPack is a one-time-use, energy-free, highly safe, and electrolyte enriched drink that based on the FO process. Thus, engineered FO process can be an effective remedy for sufficient drinking water provision during disasters and special operations.

4. CONCLUSIONS

Membrane processes, including mature pressure-driven filtration (e.g. MF, UF, NF, and RO) and emerging osmotically driven FO and thermally driven MD, can be an effective remedy for the current fresh water scarcity in Vietnam. Using these membrane processes, fresh water of adequate quality can be obtained from impaired water sources such as wastewater and seawater. Compared to conventional water treatment methods, membrane separation offers higher process efficiency (i.e. process compactness, system modularization, and reduced energy consumption). Membrane fouling caused by contaminants in the impaired feed waters is an intrinsic technical challenge to the sustainable operation of the membrane processes. Nevertheless, membrane fouling can be effectively mitigated by feed water pre-treatment and process operating condition adjustment. Besides the mature pressure-driven membrane processes, emerging FO and MD demonstrate great potential for fresh water provision in Vietnam. FO and MD can be employed in small-scale systems to converse wastewater and seawater into fresh water at low costs, thus facilitating the access to safe fresh water in remote coastal areas in Vietnam.

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