Membrane processes for the regeneration of liquid desiccant solution for air conditioning

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Abstract:

Purpose of review: Regeneration of liquid desiccant solutions is critical for the liquid desiccant air conditioning (LDAC) process. In most LDAC systems, the weak desiccant solution is regenerated using the energy-intensive thermal evaporation method which suffers from desiccant carry-over. Recently, membrane processes have gained increasing interest as a promising method for liquid desiccant solution regeneration. This paper provides a comprehensive review on the applications of membrane processes for regeneration of liquid desiccant solutions. Fundamental knowledge, working principles, and the applications of four key membrane processes (e.g. reverse osmosis (RO), forward osmosis (FO), electro-dialysis (ED), and membrane distillation (MD)) are discussed to shed light on their feasibility for liquid desiccant solution regeneration and the associated challenges.

Recent findings: RO is effective at preventing desiccant carry-over; however, current RO membranes are not compatible with hyper saline liquid desiccant solutions. FO deploys a concentrated draw solution to overcome the high osmotic pressure of liquid desiccant solutions, hence it is feasible for their regeneration despite the issues with internal/external concentration polarisation and reverse salt flux. ED has proven its technical feasibility for liquid desiccant solution regeneration, nevertheless more research into the process energy efficiency and the recycling of spent solution are recommended. Finally, as a thermally driven process MD is capable of regenerating liquid desiccant solutions, but it is adversely affected by the polarisation effects associated with the hyper salinity of the solutions.

Summary: Extensive studies are required to realise the applications of membrane processes for the regeneration of liquid desiccant solutions used for LDAC systems.

Keywords: liquid desiccant air conditioning (LDAC); liquid desiccant solution regeneration; reverse osmosis (RO); forward osmosis (FO); electrodialysis (ED); membrane distillation (MD).

1. Introduction

Increasing demands for thermal comfort in buildings together with the growing awareness of environment protection have created considerable challenges to the air conditioner industry [1-3]. Currently, most air conditioning systems are based on conventional vapor compression refrigeration. In these systems, moisture (i.e. latent load) in the air is removed by cooling the air to below the dew point temperature to facilitate water vapor condensation, and then the overcooled air needs reheating to a desired temperature prior to being introduced to the building. The overcooling and the subsequent reheating of the air consume great amounts of excess energy (i.e. electricity); thus, vapor compression air conditioners are considered to have poor energy-efficiency, particularly for applications in hot and humid climates [3-5].

Liquid desiccant air conditioning (LDAC) has emerged as a promising alternative to the conventional vapor compression air conditioners [1, 2, 5-7]. LDAC offers a novel energy- and cost-saving and environmentally friendly method to provide thermal comfort and air circulation to buildings. Unlike in conventional air conditioning systems, in LDAC air is dehumidified by using a liquid desiccant solution to absorb moisture from the air, thus obviating the need for over cooling and subsequently reheating the air and the utilization of the ozone depleting gases. Indeed, the energy consumption of a LDAC system is approximately one quarter of that of a conventional vapor compression air conditioner [3].

Liquid desiccant solution regeneration is an integral part of the LDAC process [2, 8, 9]. Liquid desiccant solution regeneration sustains the air dehumidification efficiency of the LDAC systems because the dehumidification efficiency is strongly dependent on the properties of the liquid desiccant solution. For instance, a liquid desiccant solution with a higher salt concentration and at a lower temperature exhibits a lower surface water vapor pressure, and hence a higher moisture absorption rate [3, 10, 11]. It is also noteworthy that liquid desiccant solution regeneration contributes three quarters to the total energy consumption of the LDAC process [4]. As a result, methods to regenerate liquid desiccant solutions have been the focus of many recent studies.

There has been a growing interest in deploying membrane processes for the regeneration of liquid desiccant solutions used for LDAC systems [12-17]. Membrane processes have been applied for various desalination applications including freshwater provision, oil and gas produced water treatment, brine volume minimisation, and regeneration of hyper saline solutions. Recent technological advancements in membrane fabrication and process configuration and optimisation have significantly reduced the investment and operational costs of membrane processes [18, 19].

This paper aims to provide a comprehensive review of liquid desiccant solution regeneration using membrane processes. The review begins with a brief description of the LDAC process and various commonly used liquid desiccant solutions. Then, fundamental knowledge (i.e. working principles and heat and mass transfers) of the mature as well as emerging membrane processes are provided. Based on this knowledge, the feasibility and challenges of each membrane process for the liquid desiccant solution regeneration application are critically discussed.

2. The LDAC process

2.1. Working principles of the LDAC process

A typical LDAC process entails air dehumidification, complementary evaporative cooling, and liquid desiccant solution regeneration to provide thermal comfort for buildings (Fig. 1). During air dehumidification, the air latent load and minor sensible heat is removed via the absorption into a liquid desiccant solution stream. The air sensible heat is subsequently achieved by a complementary evaporative cooler to provide dried and cooled air to buildings. The absorption of the air moisture to the liquid desiccant solution leads to an increase in the temperature but a decrease in the concentration of the solution, hence reducing its dehumidification efficiency (i.e. due to increased surface water vapor pressure). To be recycled for air dehumidification, the weak (i.e. warm and diluted) liquid desiccant solution must be regenerated.

Regeneration of liquid desiccant solution actually is a reversion of air dehumidification in which water is removed to concentrate the weak liquid desiccant solution. Most current LDAC systems utilise traditional thermal evaporation methods to regenerate the weak liquid desiccant solution [2-4, 10, 20]. During the traditional thermal regeneration, the weak liquid desiccant solution is heated to increase its surface water vapor pressure to facilitate the moisture desorption. When the heated liquid desiccant solution is brought in contact with an air stream, water in vapor form is transferred from the liquid desiccant solution to the air stream, thus concentrating the liquid desiccant solution. The concentrated liquid desiccant solution is then cooled down to restore its dehumidification efficiency before being returned to the dehumidifier.

Desiccant carry-over is a vexing technical issue associated with the traditional thermal methods to regenerate liquid desiccant solutions [3, 10]. Several configurations have been applied for the traditional thermal liquid desiccant solution regenerators. These include packed bed, spray tower, falling-film, and pressurisation and ultrasonic-atomisation regenerator [10]. These configurations can vary in their regeneration efficiency given the difference in their mass transfer rate between the heated liquid desiccant solution and the air streams. However, they all suffer from desiccant loss due to droplets carry-over as the desiccant solution is in direct contact with the air flow. Desiccant carry-over not only results in the need for desiccant solution replenishment (i.e. thus increasing the operational cost), but also poses a considerable risk to building equipment and the health of building occupants. In membrane processes, the membrane acts as a physical barrier to retain desiccant salts in the solution; therefore, desiccant carry-over can be effectively alleviated during liquid desiccant solution regeneration using membrane processes. The feasibility of and challenges associated with several typical membrane processes for regeneration of liquid desiccant solutions will be discussed in section 3.

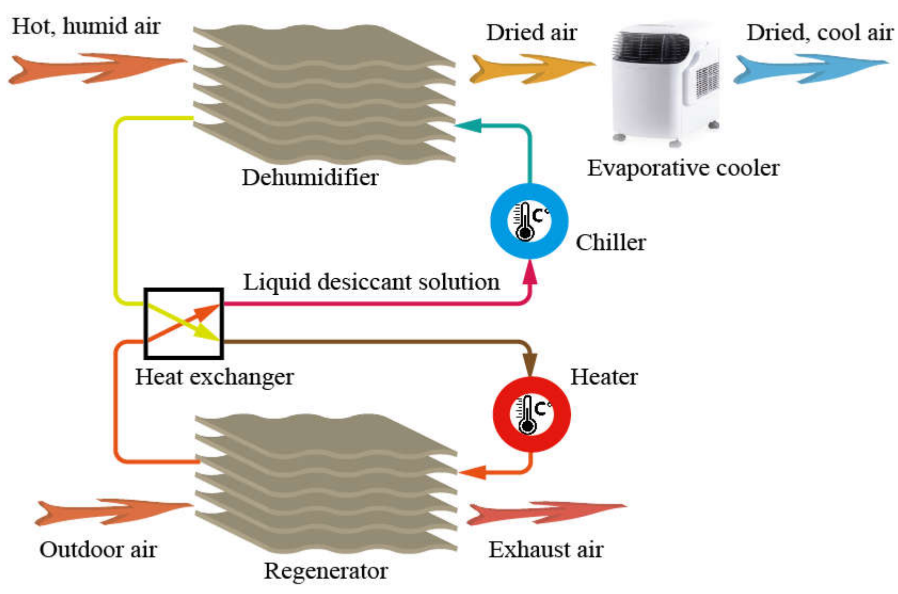

Fig. 1. The schematic diagram of a LDAC process.

2.2. Liquid desiccant solutions

An ideal liquid desiccant solution for LDAC is expected to possess several key properties, including low equilibrium vapor pressure, high energy storage density, low regeneration temperature, low viscosity, high heat transfer, non-volatile and non-corrosive, stability, and low cost [3, 10]. Amongst these, the equilibrium vapor pressure of the liquid desiccant solution directly determines the dehumidification efficiency of the LDAC system because the difference between water vapor pressures of the air and the liquid desiccant solution is the driving force for the moisture transfer in the system. The equilibrium vapor pressure depends on temperature and concentration of the liquid desiccant solution – a solution at higher concentration and lower temperature offers a lower equilibrium vapor pressure [2].

The most widely used liquid desiccant solutions for industrial dehumidifiers are glycols and solutions of halide salts (e.g. LiCl, LiBr, and $CaCl_2$). Glycols are the most traditional liquid desiccants for air dehumidification given their low equilibrium vapor pressure, low toxicity, and compatibility with a wide range of system materials. However, glycols are volatile and evaporate with air, inevitably leading to the contamination of the conditioned space and desiccant loss; therefore, their use for LDAC applications is limited. On the other hand, halide salts solutions can achieve excellent dehumidification efficiency. For example, a LiCl solution with concentration of 42% by weight can produce dried air with a very low relative humidity of 15% [3, 10]. The halide salts solutions have lower viscosity (i.e. thus reducing the energy required for pumping) and do not vaporise under LDAC operating conditions compared to glycols. Thus, they are considered the most suited liquid desiccant solutions for the LDAC systems. Amongst the three halide salts, LiCl and LiBr offer a lower equilibrium vapor pressure and hence a higher dehumidification efficiency than $CaCl_2$ [3, 10]. At the same concentration, LiCl solution can achieve a slightly lower dehumidification efficiency, but is more affordable compared to LiBr solution [3, 10]. As a result, LiCl solution is the most commonly used liquid desiccant solution for LDAC [3]. Nevertheless, LiCl solution as well as other halide salts solutions are highly corrosive and more toxic compared to glycols.

3. Membrane processes for regeneration of liquid desiccant solution

Unlike in the traditional thermal regeneration method whereby the air and the liquid desiccant solution streams are in direct contact, in membrane processes the liquid desiccant solution and another stream are separated by the membrane, and desiccant salts are retained on the feed side of the membrane. As a result, desiccant loss due to carry-over can be effectively prevented during the membrane process regeneration of liquid desiccant solutions [17]. This section will thoroughly discuss both the feasibility and technical challenges of typical membrane processes for liquid desiccant solution regeneration applications.

3.1. Reverse osmosis

Reverse osmosis (RO) is a benchmark process for seawater desalination applications [21, 22]. In the RO process, a dense and semi-permeable membrane is used to achieve the salt-water separation. Given its high water-salt selectivity, the RO membrane allows water to permeate through but rejects mostly all dissolved salts. Thus, the membrane is considered a core element of the RO process. The most commonly used membranes for commercial RO processes are cellulose acetate (CA) and thin-film polyamide composite (TFC) membranes. Detailed descriptions of the properties, advantages, and drawbacks of these RO membranes are provided elsewhere [23, 24].

To be compatible with the regeneration of liquid desiccant solutions for the LDAC systems, the RO process must achieve as high as possible salt rejection together with an acceptable water permeability. These two parameters are strongly dependent on the properties of the RO membrane and the operating conditions. It is noteworthy that there is a trade-off between salt rejection and water permeability in RO [25]. Under standard seawater RO desalination conditions (i.e. 55.15 bar applied pressure and 32,000 ppm NaCl feed solution), the RO process can attain a salt rejection of 99.8% (i.e. with respect to NaCl) at a water permeability of 4 $L \cdot m^{-2} \cdot h^{-1} \cdot bar^{-1}$ [25]. Increasing water permeability leads to a decline in salt rejection or in other words an increase in salt permeability [25]. Salt permeation through the membrane will result in salt depletion of the RO feed solution. Thus, for RO regeneration of liquid desiccant solutions, membrane with high salt rejection is preferable to that with high water permeability given the high cost of liquid desiccant solutions. Several membrane modification techniques such as fluorinated silica nanoparticles fabrication [26], mesoporous silica nanospheres incorporation [27], and heat treatment [28] have been demonstrated for salt rejection enhancement of the RO membranes. These treated RO membranes might be compatible with the regeneration of liquid desiccant solutions with negligible desiccant loss.

The high osmotic pressure of liquid desiccant solutions is likely to be a considerable technical issue for the RO process [29, 30]. As demonstrated in Fig. 2, when a semi-permeable RO membrane separates the weak liquid desiccant solution and fresh water, under the natural osmosis process, water migrates through the membrane to dilute the weak liquid desiccant solution. To regenerate the weak liquid desiccant solution, an excessively high hydraulic pressure is required on the desiccant solution side of the membrane to push water reversely through the membrane from the weak liquid desiccant solution, hence regenerating it. The rate of water transfer (J) through the RO membrane is expressed as [25]:

$$J = A(\Delta P - \Delta \pi) \quad (1)$$

where A is the water permeability coefficient, ΔP is the applied hydraulic pressure, and $\Delta \pi$ is the osmotic pressure difference between the feed and permeate sides of the membrane. To achieve a practical water flux, the applied ΔP must clearly exceed $\Delta \pi$. It is noteworthy that a LiCl solution of 25 wt.% at 25 °C has an osmotic pressure of around 180 bar [30], which is far above the workable pressure of all current RO membranes. The LDAC systems are preferably operated at LiCl concentration above 30 wt.%. Thus, RO is currently not a viable process for regeneration of liquid desiccant solutions used in the LDAC systems.

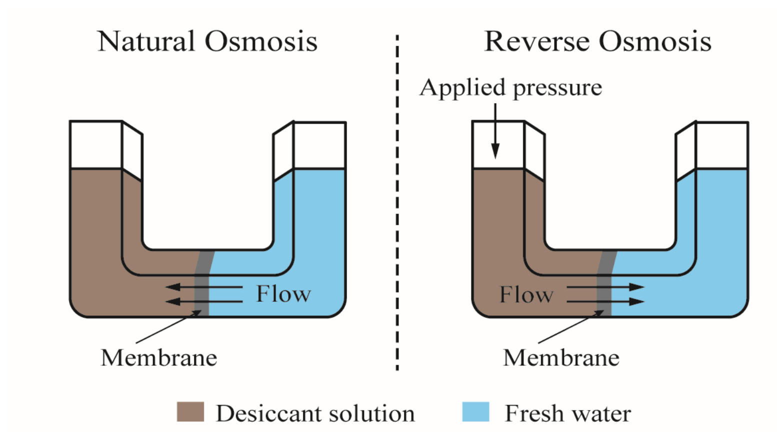

Fig. 2. Principles of reverse osmosis for the regeneration of liquid desiccant solution.

A possible solution to the problem associated with the high osmotic pressure of liquid desiccant solutions is the osmotically assisted reverse osmosis (OARO) process, also known as pressure assisted osmosis (PAO). The OARO process is actually a modification of RO, in which the fresh permeate is substituted by a draw solution (Fig. 3) [31-33]. The water transfer through the membrane in the OARO process is expressed also using the Eq. 1. Thus, the water transfer and hence the liquid desiccant solution regeneration capability of the OARO process can be tailored by regulating the draw solution concentration and the resultant osmotic pressure difference $\Delta\pi$. Using the draw solution with a sufficient osmotic pressure, the OARO process for regeneration of liquid desiccant solution can be operated at reduced applied pressure compatible with current RO membranes. It is noteworthy that the OARO process has been demonstrated for the treatment of high salinity brine [31-33], but not yet for the regeneration of liquid desiccant solutions for air conditioning.

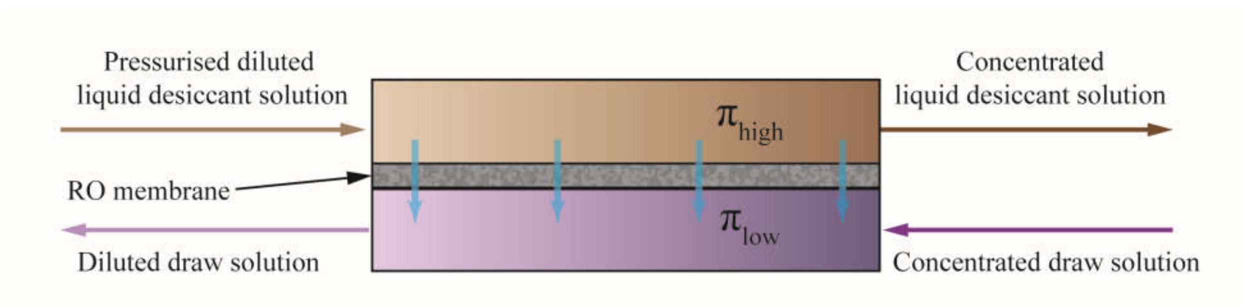

Fig. 3. The working principles of the OARO process for regeneration of liquid desiccant solution.

3.2. Forward osmosis

Forward osmosis (FO) is a promising alternative to RO for the treatment of challenging feed waters [34-38]. Unlike RO, the FO process is based on the natural osmosis under which water from a diluted solution permeates through the membrane to a concentrated solution. The FO process utilises the high osmotic pressure of a draw solution (DS) to extract water from a lower osmotic pressure feed solution (FS), and the osmotic pressure difference between the two sides of the membrane is the driving force for water transport. The FO process does not require an external hydraulic pressure like the RO process. As a result, the FO process can offer a more cost-effective and significantly lower membrane fouling treatment method compared to RO, rendering it an attractive process for the treatment of challenging feed waters like brines from RO desalination of seawater [39], oil/gas produced water [34, 40], and wastewater [41, 42].

For FO regeneration of liquid desiccant solutions, selection of proper draw solutions is of paramount importance [37, 43]. An effective draw solution for FO applications to regenerate liquid desiccant solutions needs to satisfy several criteria: (1) exhibits a high enough osmotic pressure to overcome that of liquid desiccant solutions, (2) is readily available at reasonable costs, (3) has low viscosity, and (4) demonstrates a low reverse salt flux. The latter two criteria are related to two intrinsic phenomena of the FO process: concentration polarisation and reverse salt flux.

Water flux (J_w) through the membrane in an ideal FO process is expressed as:

$$J_w = A(\pi_{D,b} - \pi_{F,b}) \tag{2}$$

where A is the membrane water permeability, and $\pi_{D,b}$ and $\pi_{F,b}$ are the bulk osmotic pressures of the draw solutions and the feed, respectively. In practice, the FO process severely suffers from internal concentration polarisation (ICP) and external concentration polarisation (ECP). These concentration polarisation effects lead to a reduction in the osmotic pressure of the draw solution and an increase in that of the feed solution close to the membrane surfaces compared to the bulk values (Fig. 4). As a result, the concentration polarisation effects considerably reduce the FO water flux [44-47]. The concentration polarisation effects are envisaged to be discernible for the FO regeneration of liquid desiccant solutions given the hyper salinity of both the feed and the draw solutions.

The reverse flux of the draw solute through the membrane to the feed solution is another major issue for the FO regeneration of liquid desiccant solutions. An ideal FO membrane is expected to allow only the permeation of water while preventing completely the passage of salts through it. However, the practical FO process to some extent experiences the reverse diffusion of salts from the draw solution to the feed because of the membrane's non-complete salt rejection and the concentration gradient between the draw and the feed solutions [48-50]. The reverse diffusion of the draw solute results in a decline in the concentration gradient (hence reducing water flux) and more seriously the contamination of the liquid desiccant solution. It is important to note that the reverse salt flux is proportional to the concentration gradient between the draw and the feed solutions and the diffusion coefficient of the draw solute. While the former directly determines the FO process water flux, the latter affects the concentration polarisation effects (draw solute with high diffusion coefficient helps reduce the concentration polarisation effects). Thus, there is a trade-off between reverse solute flux and water flux during the FO process.

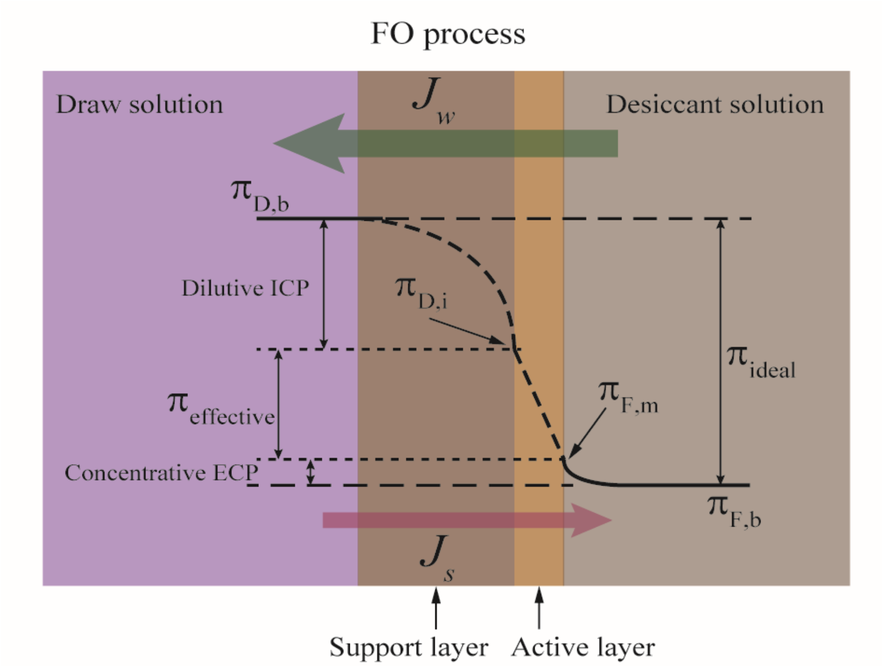

Fig. 4. Internal and external concentration polarisation of the FO process.

The issue of reverse solute flux contamination could be effectively alleviated when the same solute is employed for both the liquid desiccant solution and the draw solution (i.e. at a higher concentration). Indeed, this alteration of the FO process has been used in commercial LDAC systems. In these systems, a weak and a concentrated liquid desiccant solution (of the same solute) are separated by an FO membrane. The membrane facilitates the transfer of water from the weak solution to the concentrated solution and in tandem the diffusion of the solute in a reverse direction. As a result, the weak liquid desiccant solution is regenerated without being contaminated.

3.3. Electro-dialysis

Electro-dialysis (ED) is an electrically driven membrane separation process in which cation and anion exchange membranes are used to facilitate the selective transport of cations and anions under an electric field [51-53]. Due to their selectivity, cation exchange and anion exchange membranes allow the passage of only cations or anions, respectively. In an electro-dialyser, cation exchange and anion exchange membranes are placed alternatively between the anode and the cathode (Fig. 5). Under the influence of the electric field, cations and anions respectively migrate through the membranes to the anode or the cathode, leading to an increase in salt concentration of the regenerated solution and simultaneously a decline in the spent solution concentration. Thus, the weak liquid desiccant solution can be regenerated without the need for heating the solution as in the thermal regeneration method, and hence the energy consumption of liquid desiccant regeneration can be reduced [9, 14, 54]. It is noteworthy that during the ED process, coinciding with the migration of cations and anions is the transport of water through the membranes due to the osmotic pressure difference between the regenerated and the spent solutions [54, 55]. This water transport results in the dilution of the regenerated solution, and it might negatively affect the regeneration efficiency of the ED process.

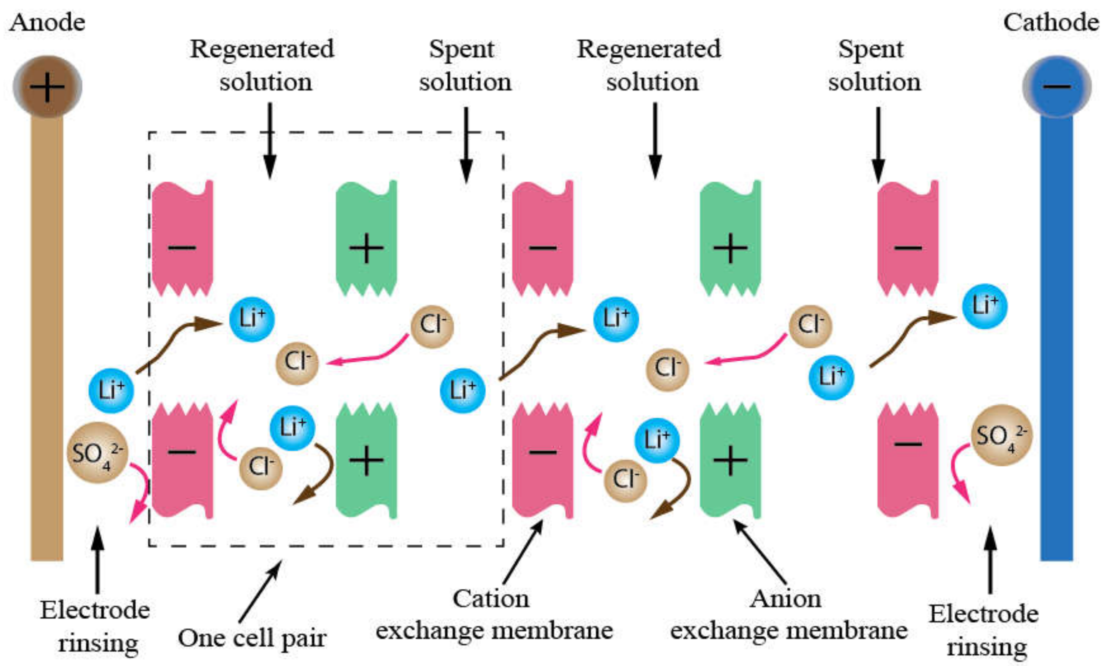

Fig. 5. A schematic diagram of an ED process for regeneration of LiCl liquid desiccant solution (adapted from [54]).

Extensive studies have been conducted to elucidate the performance of the ED process for the regeneration of liquid desiccant solutions [14, 54-60]. As a notable example, Guo et al. [54] systematically examined the influences of the ED operating conditions (e.g. current density, liquid desiccant solution initial concentration, circulation flow rates, and the concentration difference between the regenerated solution and the spent solution) on the regeneration capacity (i.e. increase in regenerated solution concentration) of a bench-scale ED system with LiCl solution. The authors reported that ED regeneration capacity increased with decreased circulation flow rates, increased current density, and lowered regenerated solution initial concentration. Particularly, the difference in concentration between the regenerated and spent solutions exerted a profound impact on the system regeneration capacity due to the influences of osmosis and salt diffusion. Thus, the ED system could only regenerate the LiCl solution with a concentration difference between the regenerated and the spent solutions below 5.86 wt.% [54]. The influences of ED operating conditions on the system energy efficiency have also been investigated by Cheng and Jiao [58], Chen et al. [61], and Xu et al. [51]. The results from these studies demonstrated that the ED regeneration process of liquid desiccant solutions exhibits limited energy efficiency (i.e. 20–70% of the applied current is useful utilised), and the process energy efficiency decreases when regenerating liquid desiccant solutions with higher initial concentrations.

Despite its great promise, more studies are needed prior to the realisation of ED for the regeneration of liquid desiccant solutions. Novel approaches are required to improve the energy efficiency of the ED process, especially for the regeneration of liquid desiccant solutions in LDAC systems given their hyper saline nature. Recycling the spent solution used in the ED regeneration process of liquid desiccant solutions is also worth considering. Because the concentration difference between the regenerated and the spent solutions critically affects the ED process regeneration capacity and energy efficiency, the spent solution eventually needs being regenerated. In this context, a multi-stage ED or a thermal evaporation process might be explored. The following section will discuss the viability of the thermally driven membrane separation process for liquid desiccant regeneration applications.

3.4. Membrane distillation

Membrane distillation (MD) is a hybrid separation process that combines thermal distillation and membrane separation [62-66]. In the MD regeneration process of liquid desiccant solutions, a microporous hydrophobic membrane is used to separate the liquid desiccant solution from a fresh permeate water stream. Due to its hydrophobic nature, the membrane only allows the transport of water vapor but not liquid water and hence dissolved desiccant salts through the membrane pores. In other words, the MD process can theoretically regenerate liquid desiccant solutions without any desiccant solution loss as experienced in the traditional thermal regeneration process. More importantly, unlike in other membrane processes (e.g. RO, FO, and ED), the two process streams (e.g. liquid desiccant solution and fresh water permeate) in MD are hydraulically separated; thus, the MD process is not affected by the osmotic pressure of the liquid desiccant solutions. Finally, as a thermally driven separation process, MD can be operated at mild temperature sourced from low-grade waste heat and solar thermal energy [63, 67-70]. It is noteworthy that the demand for air conditioning often coincides with the abundant availability of low-grade heat sources. As a result, the energy consumption of LDAC systems can be reduced by deploying the low-grade heat powered MD process for the regeneration of liquid desiccant solutions.

The driving force for water transfer in the MD process is the water vapor pressure difference between two sides of the membrane. To establish the water vapor pressure difference, several methods can be applied corresponding to various MD configurations (Fig. 6). In direct contact MD (DCMD), a cold fresh water stream is circulated on the membrane permeate side to condense water vapor permeating through the membrane from the feed stream. The condensation of water vapor into distillate occurs inside the membrane module; thus, DCMD is the simplest and the most widely used MD configuration. However, because the hot feed and the cold permeate streams are in direct contact with the thin membrane, there exists a considerable heat loss due to conduction from the feed to the permeate stream in DCMD. Thus, DCMD exhibits the lowest thermal efficiency amongst the MD configurations. The conduction heat loss is alleviated in the air gap MD (AGMD) configuration by inserting an air gap between the hot feed and the coolant streams. The air gap, however, increases the resistance to the transfer of water vapor. As a result, AGMD has a higher thermal efficiency but lower water flux than DCMD. Increased water flux and thermal efficiency can be achieved by using sweeping gas and vacuum in sweeping gas MD (SGMD) and vacuum MD (VMD), respectively. Nevertheless, additional equipment (e.g. gas blowing fans, vacuum pumps, and condensers) is required for water vapor condensation in SGMD and VMD, hence increasing the process investment and operational costs.

The feasibility of MD for regeneration of liquid desiccant solutions used for LDAC systems has been demonstrated at both bench-scale and pilot-scale levels mostly using DCMD and VMD configurations [13, 71-75]. Duong et al. [13] employed a bench-scale DCMD system to regenerate a LiCl liquid desiccant solution for used for air conditioning. The DCMD process at feed temperature of 65 °C could increase the LiCl concentration up to 29% without any observable LiCl loss [13]. Lefers et al. [73] utilised a bench-scale VMD system to manifest the capability of MD for regeneration of liquid desiccant solutions (e.g. $CaCl_2$ and $MgCl_2$ solutions) and in tandem fresh water recovery. The VMD process proved to be able to regenerate the liquid desiccant solutions and provide fresh water of sufficient quality for agricultural irrigation and drinking [73]. A pilot VMD process using solar thermal energy for regeneration of liquid LiBr desiccant solution was examined by Choo et al. [75]. The experimental results showed the heavy dependence of the VMD process performance indicators (e.g. water flux and thermal performance ratio) on the process operating conditions (e.g. the feed concentration, heat source temperature, and feed flow rate) [75].

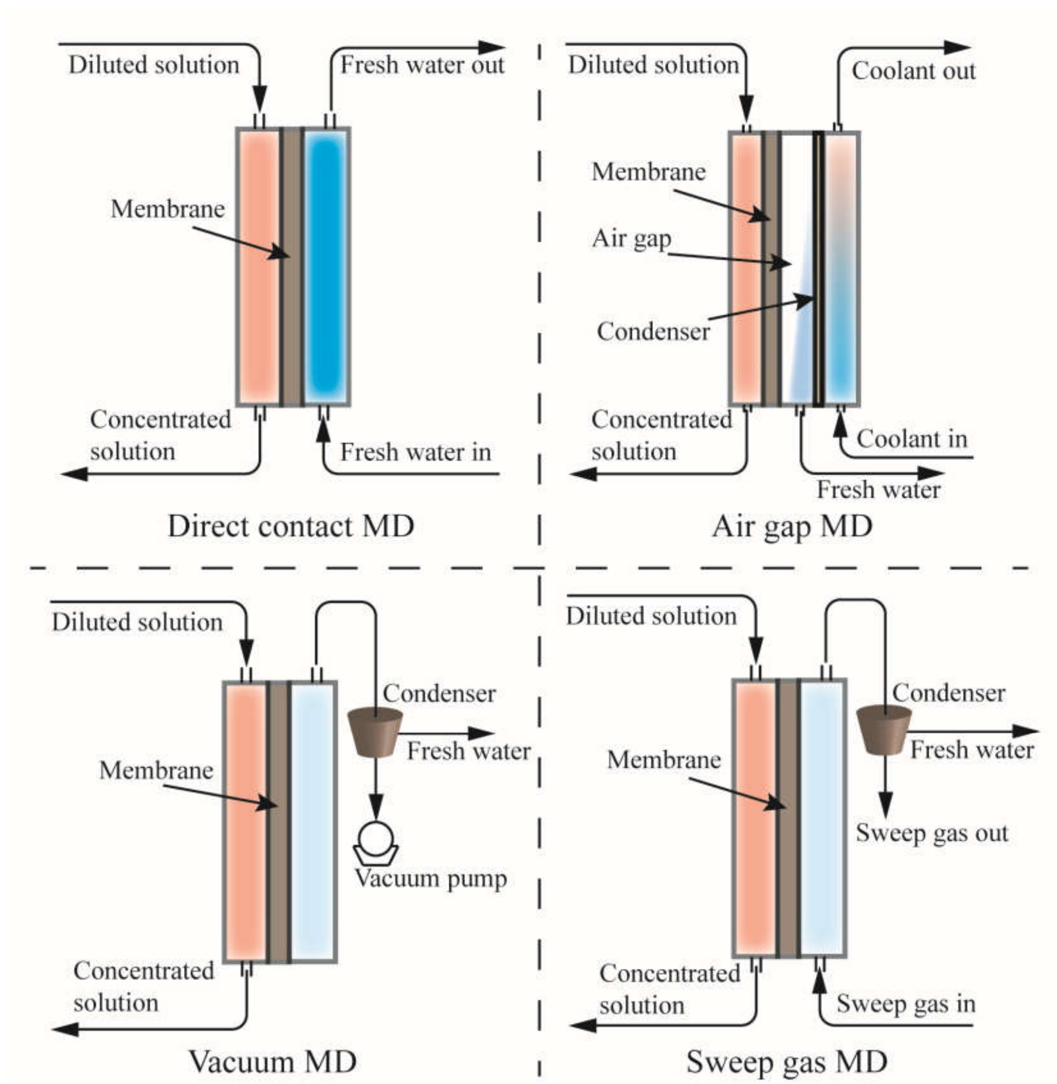

Fig. 6. Schematic diagrams of the four basic MD configurations.

The most considerable technical challenge to MD regeneration of liquid desiccant solutions is the polarisation phenomena, particularly the concentration polarisation effect [13, 76]. Temperature and concentration polarisation effects are intrinsic problems for the MD process. The temperature polarisation reduces the temperature while the concentration polarisation increases the salt concentration at the membrane surface compared the those in the bulk feed solution; therefore, they reduce the MD process water flux. Given their hyper salinity, the MD process of the liquid desiccant solutions is envisaged to suffer severe polarisation effects. Indeed, Duong et al. [13] experimentally showed that concentration polarisation could reduce the water flux of an MD process with a LiCl 20 wt.% solution feed by over a half. Therefore, methods to alleviate the severity of polarisation effects play a crucial role in realising the MD process for regeneration of liquid desiccant solutions used in LDAC systems.

4. Conclusions

The applications of four key membrane processes for regeneration of liquid desiccant solutions used for LDAC systems are comprehensively reviewed. Given its excellent salt-water separation efficiency, RO can effectively prevent desiccant carry-over, which is a vexing issue for conventional thermal desiccant solution regeneration methods. However, the current RO process is not viable for regenerating the liquid desiccant solutions due to their extreme osmotic pressure. The osmotically assisted RO process might overcome the extreme osmotic pressure of liquid desiccant solutions, but there have not been any experimental demonstrations of this process for the regeneration of liquid desiccant solutions. The FO process harnesses an osmotic pressure gradient induced by a concentrated draw solution to drive water through the membrane; therefore, it is compatible with liquid desiccant solution regeneration. Internal and external concentration polarisation and reverse salt flux are considerable challenges to the FO regeneration of liquid desiccant solutions. Therefore, future research on FO regeneration of liquid desiccant solutions should be focused on addressing these challenges. The ED process employs cation- and anion-exchange membranes and an electrical field to regenerate the liquid desiccant solutions. ED demonstrates its technical feasibility for liquid desiccant solution regeneration, nevertheless more research into the process energy efficiency and the recycling of spent solution are recommended. Finally, as a thermally driven membrane process, MD has proven to be a promising process for regeneration of liquid desiccant solutions. Similarly to ED, further studies are required to address the issue of the polarisation effects particularly concentration polarisation in MD regeneration of liquid desiccant solutions.

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Conflict of interest statement

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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Recently published papers of interest have been highlighted as:

• Of importance

•• Of major importance

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