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Energy Efficiency In Air Conditioning Through The Desiccant Technology - A Review

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Abstract : *A thermally driven air conditioner that uses liquid desiccants as the working fluid may be an attractive alternative to the compressor-based technology that is now used in most HVAC applications. The operation of a liquid-desiccant air conditioner is first explained and several basic concepts are reviewed. This review focuses on the development of liquid- desiccant conditioners and regenerators that are better suited to comfort conditioning. This includes work on conditioners and regenerators that use low flow rates of desiccants and have internal heat exchange. These conditioners and regenerators will have lower pump and fan power than conventional one, and will be much less likely to introduce desiccant droplets into the process air. Through a literature review, the feasibility of the desiccant material and its properties are highlighted. Different types of direct and indirect dehumidifiers and regenerator are explained along with detailed performance parameters. The advantages it can offer in terms energy and cost savings are underscored.*
Keywords: *Desiccant, liquid desiccant system, dehumidifier, regenerator and LAMEE.*

I. Introduction

One of the prime concerns of the present age is the day by day increase in energy consumption for space cooling applications. Nowadays, space air conditioning in most parts of the world is done by conventional vapour compression refrigeration, based air conditioners which require large amount high grade electrical energy for its running. The use of vapour compression refrigeration based air conditioners has led to increased CFC levels resulting in depletion of the ozone layer. Production of electricity in power stations has also been created many environmental issues, like global warming. Further, the constant increase in the demand for space cooling applications, due to development of many parts of the world, has compelled researchers to investigate alternate technologies for air conditioning to overcome the above mentioned issues. The desiccant cooling system maintains required indoor comfort by optimal use of thermal energy with least electrical power. The desiccant cooling can be used either in a standalone system or coupled judiciously with a vapour compression refrigeration air conditioning system and free energy like solar or industrial waste heat to achieve high performance over wide range of operating conditions. In hybrid system, the desiccant dehumidifier efficiently removes the moisture from fresh ventilated air before it enters into the conditioned space while the vapour compression system removes only sensible heat then after. This type of arrangement rules out the requirement of low dew point temperature of evaporator cooling coil and subsequently reheating. It also avoids the condensation problem, occurs during excess humid ambient conditions. The use of hybrid desiccant cooling system not only controls the humidity but also reduce operating costs and electric power demand. Thus, the desiccant cooling was suggested as supplement to conventional vapour compression cooling or evaporative cooling due to its energy and cost saving in hot and humid environment conditions by controlling temperature and humidity independently. Its operating costs can be reduced further by the use of low grade heat energy like solar, waste heat and natural gas. The peak cooling demand in summer is associated with high solar radiation which offers an excellent opportunity to utilize solar assisted desiccant cooling technology. Desiccant cooling can meet the current demands of occupant comfort, energy saving along with operational cost reduction and finally and the most important is environmental protection. The main objective of this review is to find, an optimal use of desiccant cooling system. It also summarizes recent research developments related to desiccant cooling system and to provide information for its potential application.

II. Overview Of Desiccant Cooling

A. Desiccant Cooling system

The main purpose of the desiccant is to attract the water vapour from the air because of the difference in vapour pressure between the air and the surface of the desiccant solution. Dehumidification process is said to occur when the vapour pressure of the surface of the desiccant is less than that of air and continues until the desiccant reaches equilibrium with air as shown in figure 1. Desiccants can be regenerated at low temperature, from approximately 50 to 80 degree C. Thus, the regeneration process could be driven by heat sources with a relatively low temperature of approximately 70 degree C, such as solar energy, waste heat, and geothermal power.

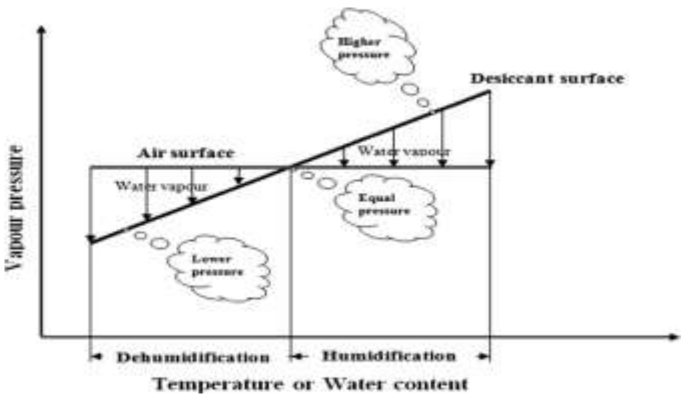


Figure. 1. Relationship between vapor pressure and water content in dhimmification process.

B. Desiccant Materials

The desiccants materials are of two types namely solid and liquid desiccant materials. Several types of solid materials can hold water vapour; they are silicas, polymers, zeolites, aluminas, hydratable salts, and mixtures. Liquid desiccant materials are: calcium chloride, lithium chloride, lithium bromide, Tri-ethylene glycol, and a mixture of 50% calcium chloride and 50% lithium chloride.Figure.2 shows the main types of solid and liquid desiccants. These liquid desiccants have general properties, but their requirements are not fully answered by any single desiccant. These requirements include low vapour pressure, low crystallization point, high density, low viscosity, low regeneration temperature, and low cost as shown in Table 1. Many studies have examined the performance of liquid desiccants types under various parameters, such as inlet mass flow rate, temperature, and humidity ratio of the air as well as the inlet mass flow rate, temperature, and concentration of the desiccant solution. Hassan and Salah [27] proposed a desiccant with a mixture of 50% weight of water calcium chloride and
20% calcium nitrate. They studied the physical properties of the mixture, such as viscosity, vapour pressure, density, and heat, and the mass transfer process. The results of their study showed a significant increase in vapour pressure of approximately 14.7, 20.6, 34.4, and 47.3 mm Hg at
30, 40, 50, and 60 degree C, respectively. Li et al. [28].

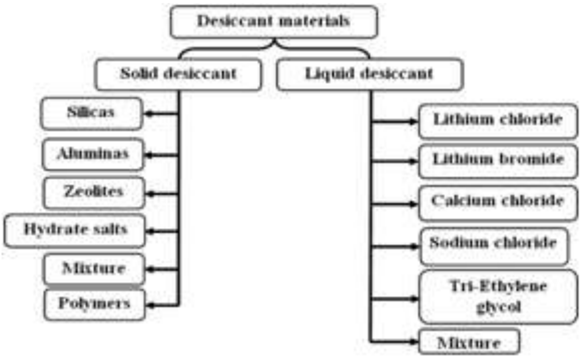


Figure. 2. Main types of solid and liquid desiccants materials

C. Desiccant characteristics

The behaviour of all desiccant system components is profoundly influenced by the operating characteristics of the desiccant materials they contain. Recognizing this fact, re- search institutions and manufacturers have focused on material science to develop desiccants which are especially suited to air-conditioning applications. These efforts have had two primary goals to develop desiccants which:

1. Use less energy for reactivation and therefore need less energy for cooling.

2. Are more stable and fault-tolerant and therefore require less maintenance.

Important considerations in choosing or designing the optimal liquid desiccant solution for a dehumidification application:

- High vapour pressure of water in solution
- Low vapour pressure of solute
- Performance of solution steady over large concentration range
- Non-corrosive and chemically stable
- Low Viscosity
- High solubility
- Low regeneration temperature
- Non-toxic, harmless
- Low Cost

Lithium chloride (LiCl), Calcium Chloride (CaCl2), Lithium Bromide (LiBr), and tri-ethylene glycol (TEG) are common liquid desiccant materials meeting the above performance characteristics to varying degrees. LiCl and CaCl2 dominate the most recent research efforts into liquid desiccant dehumidification systems.

Table.1

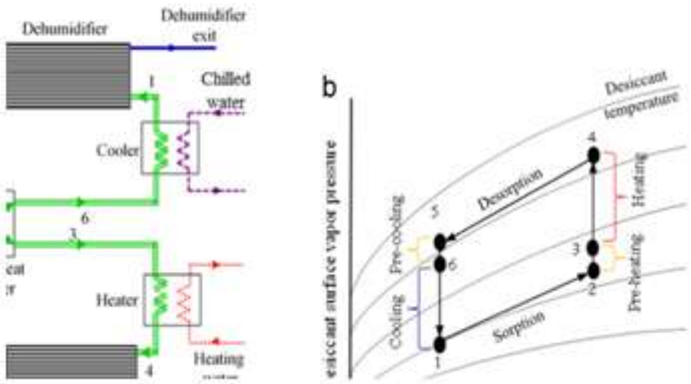
Main characteristics of liquid desiccants types			
Characteristics	TEG	LiCl and LiBr	CaCl2
Suitability of equilibrium characteristic	Moderate dehumidification when regenerated at 65-80 °C Requires high circulation rate between dehumidifier and regenerator	Good dehumidification with regeneration temperature above 80 °C Does not require high circulation rate between dehumidifier and regenerator	Poor dehumidification Regeneration possible at temperature of about 60°C Does not require high circulation rate between dehumidifier and regenerator
Loss desiccant through evaporation	Present during regeneration Minimal during dehumidification	No loss	No loss
Possibility of crystallization corrosion hazard	Does not crystallize Moderate, requires inhibitors and hydrogenation (PH) control	Present High, requires inhibitors and hydrogenation (PH) control	Present more likely for lithium salts Moderate, requires inhibitors and hydrogenation (PH) control
Toxicity of vapour	Non toxic	Does not evaporate	Does not evaporate
Cost	High	High	Low

D. There are two types of desiccant cooling systems: - E. Solid Desiccant Cooling System

The solid desiccant system is consisting of desiccant wheel, by placing a thin layer of water affinity material, such as silica gel, on a support structure. The desiccant wheel rotates slowly, desiccant material absorbs the moisture from ambient air and dehumidification takes place due to difference of vapour pressure between desiccant material and ambient air. The desiccant material to be used again for dehumidification it has to be regenerated. Heat is added to the desiccant material from external heat source to increase the vapour pressure. Then desiccant material is passed through regeneration process where it rejects moisture to ambient air. However, it has been observed that there is pressure loss in desiccant wheel, which makes it less energy efficient.

F. Liquid Desiccant Cooling System

Liquid desiccant cooling system overcomes the limitation of pressure drop of solid desiccant cooling system. The components of a LDAC system are dehumidifier, regenerator, cooling equipment, and heating equipment. Hot-humid air enters the dehumidifier, where it is dried by a cold and concentrated desiccant solution (see state (1) in Figure.3. below. The desiccant solution leaves the dehumidifier (state(2) at a lower concentration (and possibly higher temperature) than it entered the dehumidifier, and thus it has to be regenerated before it can be reused in the dehumidifier. The regeneration of the dilute desiccant solution takes place in a regenerator, where water vapour transfers from the dilute desiccant solution stream to a regeneration air stream. Thus, the dilute solution is heated to a specific set point temperature before it is delivered to the regenerator (state (4)). The concentrated desiccant solution leaving the regenerator (state (5)) is warm and has high surface vapour, and therefore it needs to be cooled to a specific set point temperature in order to reduce its vapour pressure below the vapour pressure of the hot-humid air that is to be dehumidified.



III. Energy Exchanger Are Of Two Types

A. Direct-contact energy exchangers

In direct-contact dehumidifiers/regenerators, heat and water vapour transfer take place between air and desiccant solution streams through direct contact. Most of the early research con- ducted on liquid desiccant dehumidifiers/regenerators focused on direct-contact designs, which is mainly attributed to their simplicity compared to indirect-contact designs. Due to direct contact small liquid desiccant droplets might be carried over by the process air into the indoor environment. This carryover of desiccant droplets in air streams lead to corrosion of duct and affect the indoor air quality. The designs of direct- contact dehumidifiers/regenerators presented in this section are:

1) Packed bed: The most commonly used and studied liquid desiccant dehumidifier/regenerator, among direct-contact designs, is the packed bed. As shown in Figure. 4 (a), desiccant solution is usually distributed from the top of the packed bed and flows over the packing where it comes in a direct contact with the air stream. The packed bed dehumidifier/regenerator can be either adiabatic or internally cooled/heated. In an adiabatic packed bed, Figure. 4(a), the temperature of the desiccant solution changes as it flows through the dehumidifier/regenerator due to the heat transfer with the air stream and the source/sink of phase change energy which accompanies the moisture transfer. In an internally cooled/heated (i.e. isothermal) packed bed, the solution is continuously cooled/heated by a third fluid (e.g. water in Figure. 4(b)) as it passes through the packed bed.

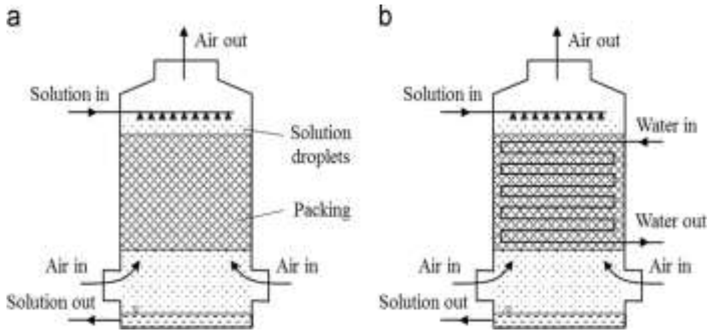


Figure. 4. Conceptual schematics for (a) adiabatic and (b) isothermal packed beds.

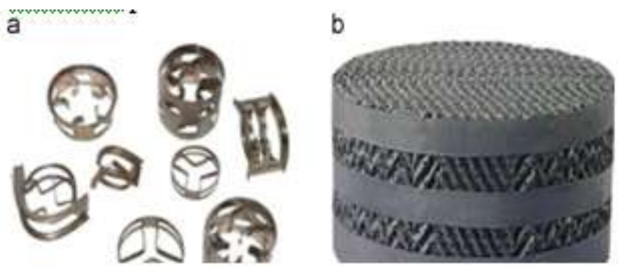


Figure. 5. Photos for (a) random packing and (b) structured packing.

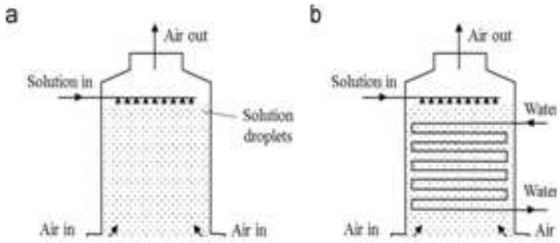


Figure. 6. Conceptual schematics for (a) adiabatic and (b)isothermal spray towers.

As a result, the solution experiences no (or small) change in its temperature as it passes through the packed bed, and consequently the potential for mass transfer is improved compared to an adiabatic packed bed. Bansal et al. [20] compared the experimental performances of an adiabatic and an internally-cooled packed-bed dehumidifiers. It was found that the effectiveness of the internally-cooled packed bed is

28 to 45 % higher than the effectiveness of the adiabatic packed bed, depending on the operating conditions. The two types of packing which are commonly used in packed beds are the random and structured packing as shown in Figure

5(a) and (b), respectively, where the random packing is less expensive than the structured packing. Results showed that random packing experiences higher pressure drop compared to structured packing. In a packed-bed dehumidifier/regenerator, the air and solution streams may have a cross- flow, a counter-flow, or a parallel- flow configuration. Although the packed-bed design is characterized by several advantages, the transfer of liquid droplets to the air stream (called carryover) is a drawback of the packed-bed design especially when it is operated under high flow rates. Thus, a mist eliminator is usually installed at the air exit to capture any entrained desiccant droplets, which increases the air-side pressure drop, as well as the capital and operating costs of the packed bed LDAC system.

2) Spray tower: In a spray-tower dehumidifier/regenerator, the desiccant solution is sprayed as small droplets from distributors located at the top of the spray tower, as shown in Figure. 7. The air is in direct contact with the desiccant droplets as they free fall within the tower. The heat and moisture transfer occurs at the interface between the surface of the desiccant droplets and the air. Unlike the packed-bed design, no contact surfaces are used to aid the distribution of desiccant solution in the spray tower. The spray tower can be operated at lower solution flow rates and air-side pressure drops compared to the packed bed, due to the larger air-to-solution contact area and the absence of packing in the spray tower, respectively. However, there is a higher risk for desiccant droplet carryover in the spray tower compared to the packed bed.

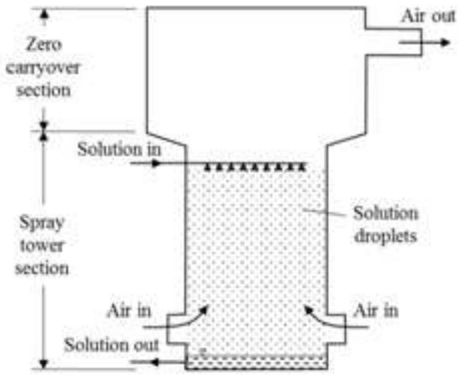


Figure. 7. A conceptual schematic for a zero-carryover spray tower proposed by Kumar et al.[24].

The size of desiccant droplets, which depends on the type of the distributor, significantly impacts both the heat and mass transfer and the desiccant droplets carryover in the spray tower. The smaller the desiccant droplets, the larger the surface area for heat and mass transfer, while the higher the risk for desiccant droplet carryover in air streams[29]. The desiccant droplets are the smallest when a nozzle distributor is used[24]. To eliminate the problem of desiccant droplet carryover, Kumar et al.[24.]. proposed a spray-tower design which can be operated at zero desiccant droplets carryover without inducing any additional pressure drop. This is achieved by installing an additional section the zero carryover section at the top of the spray tower, as shown in Figure. 7. The air velocity in the zero-carryover section is reduced by around 75% compared to the air velocity in the spray tower, and thus any entrained desiccant droplets in the air stream fall back in the spray tower due to the reduction of the uplifting drag force on the desiccant droplets[24]. 3) Falling film: In the falling-film design, a desiccant solution film is distributed over plates or tubes[26], and the air flows over the solution film as can be seen from Figure.8. The advantages of this design is that it experiences lower air-side pressure drop compared to the commonly used packed bed. Moreover, there is a lower risk of desiccant droplets carryover in the falling-film design compared to the spray-tower design. The influences of wetted area and film thickness on the heat and mass transfer performance of falling-film designs were experimentally investigated by Qi et al. [5]. It was found that the mass transfer performance of a falling-film flat-plate regenerator increases as the wetted area increases, and the performance decreases as the film thickness increases.

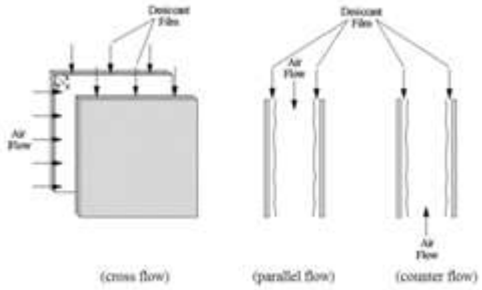


Figure.8. Schematics for vertical flat-plate falling- film exchangers[26].

B. Indirect-contact energy exchangers

To overcome this carryover problems, recently, selectively permeable membranes had been combined with the liquid desiccant air dehumidification to form a new kind of liquid desiccant air dehumidification system, the so-called or liquid-to-air membrane energy exchanger (LAMEE). Indirect- contact desiccant dehumidifiers/regenerators are a more recent development than direct-contact dehumidifiers/ regenerators. The main advantage of indirect-contact over direct- con- tact dehumidifiers/regenerators is the elimination of desiccant droplet carryover which is prominent in direct-contact dehumidifiers/regenerators. There are different types of indirect- contact dehumidifiers/regenerators, but all are membrane-based technologies, as follows:

C. Liquid-to-air membrane energy exchanger (LAMEE)

Air and solution streams are separated from each other in liquid-to-air membrane energy exchangers (LAMEEs) using hydrophobic semi-permeable membranes. These membranes allow the transfer of water vapour between the air and solution streams, but prevent the transfer of liquid desiccant. The attraction forces between liquid molecules are larger than their attraction to the solid surface of a hydrophobic semi-permeable membrane; as a result, the surface tension forces between the liquid molecules creates an interface between the liquid and the membrane as shown in Figure[9]. This prevents the migration of any liquid droplets across the membrane to the air side, and thus there is no risk of desiccant droplets carryover in air streams at moderate pressure difference between the liquid and air streams. There are two structures of the LAMEE: at-plate and hollow- fiber. The flat-plate LAMEE (see Figure.10(a)), has a similar structure to a flat-plate heat exchanger and the only difference is that semi- permeable membranes are used to separate the air and solution streams. The effectiveness of the flat-plate LAMEE is the highest when it operates under counter-flow configuration; however, the manufacture of a counter-flow flat-plate LAMEE is complex. Thus, a counter-cross flow configuration was proposed. as shown in Figure.10.(a), where the LAMEE operates as cross-flow only at the solution inlet and outlet, and operates as counter-flow for most (90%) of the LAMEE. The counter-cross flow configuration is the most widely used flat-plate LAMEEs during recent years [4,6,9,10].

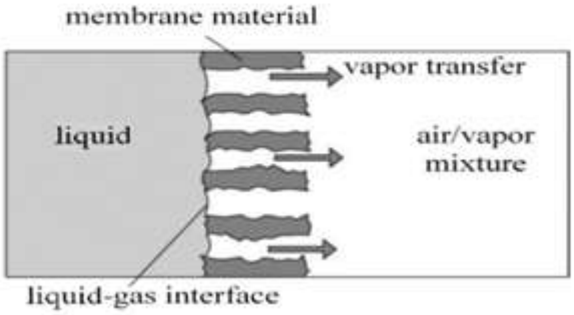


Figure.9. A conceptual schematic for water vapor transfer between air and desiccant solution stream through a semi- permeable hydrophobic membrane.

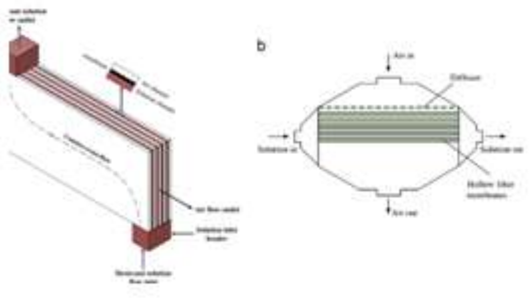


Figure.10. Schematics for (a) counter-cross-flow flat- plate LAMEE [6], and (b) cross-flow hollow-fiber LAMEE [12].

The hollow-fiber LAMEE (see Fig. 10(b)), has a similar structure to a shell and tube heat exchanger, where the solution flows through hollow-fiber semi-permeable membranes and the air flows outside the hollow fibers in the shell side. The hollow fibers can have either a staggered or parallel alignments, where the parallel alignment is recommended because it results in lower air-side pressure drop compared to the staggered alignment. Isetti et al. [8] proposed and tested an internally-cooled LAMEE (Figure. 11), which operates under air dehumidification mode. In this design, the air flows inside hollow-fiber membranes which are surrounded by desiccant solution, and the refrigerant flows in rectangular solution channels. A novel design for an internally-cooled flat-plate LAMEE was recently proposed and tested by Abdel-Salam et al.[3] , as shown in Figure. 12.This has a similar design to flat-plate LAMEE presented in Figure10. (a), and the main difference is that there are water-cooled tubes which pass through the solution channel as shown in Figure. 12(b). Preliminary results by Abdel-Salam et al. [3] showed that the moisture removal rate and sensible cooling capacity of the internally-cooled flat-plate LAMEE are 54% and 140%, respectively, compared to an adiabatic flat-plate LAMEE is presented in a review by Abdel-Salam et al. [4].

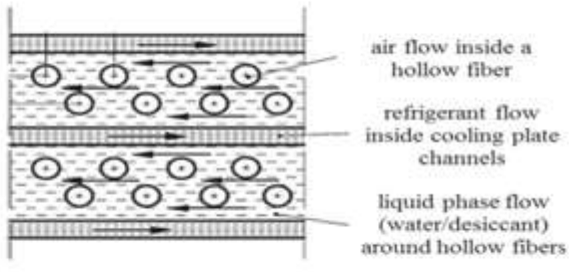


Figure. 11. A schematic for the internally-cooled LAMEE [8].

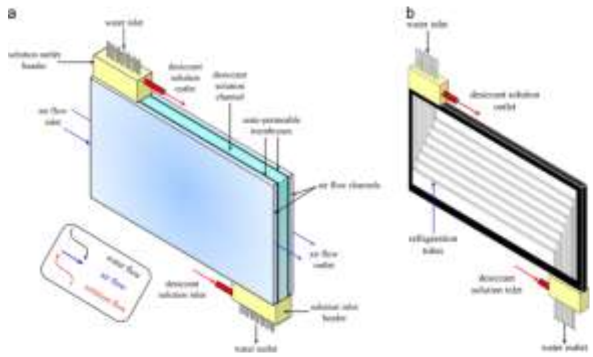


Figure. 12. A schematic for the internally-cooled flat- plate LAMEE proposed by Abdel-Salam et al. [3].

The research conducted on the fundamentals of flat-plate and hollow-fiber LAMEEs is presented in a comprehensive review by Abdel-Salam et al. [6].

1) Electrodialysis regenerator: The operation of an electrodialysis regenerator is based on the use of ion-exchange membranes, where the electrochemical potential is the driving force. The electrodialysis regenerator consists of several cell pairs; each cell pair consists of cation and anion exchange membranes, and a concentrate and dilute solution cells as shown in Figure.13. When an electrolyte solution passes through the cells and an electric potential is applied between the cathode and anode, the cations migrates through the cation exchange membrane towards the cathode, while the anions migrate towards the anode through the anion exchange membrane. Thus, the salt solution is concentrated and diluted in the concentrate and dilute cells, respectively. The electrodialysis technology is widely used in sea-water-desalination applications, while only a few studies have considered it for desiccant solution regeneration. The advantages of the electrodialysis regenerator is the elimination of the need for heating the solution prior to regeneration, which means that the LDAC system can be operated using lower cooling energy and without the need for heating energy. Moreover, the electrical energy required to operate the electrodialysis regenerator can be provided using solar photovoltaic (PV) panels, and the price of PV is decreasing and the efficiency is increasing. Although the electrodialysis regenerator is not mature yet, it is a promising regeneration technology [12,16], and its performance could be improved through future research.

2) Reverse-osmosis regenerator: Osmosis refers to the transfer of solvent molecules through a semi-permeable mem- brane from a high-concentration side to a low-concentration side in order to reach the same concentration on both sides. The operation of reverse-osmosis in the regeneration of dilute desiccant solution is based on applying a high pressure on the dilute solution channel. This results in the migration of some water molecules from the high-pressure side to the low-pressure side across the semi-permeable membrane, as shown in Figure.14. The semi-permeable membranes used in the regeneration of dilute desiccant solution only allow the diffusion of water molecules, and no salt ions transfer through the membrane. This results in the increase of solution concentration at the high-pressure side of the membrane (i.e. left side of the membrane in Figure.14). All types of indirect- contact dehumidifiers /regenerators are membrane-based, which eliminate desiccant droplet carryover into the air stream. The driving potential for

water vapour transfer in LAMEEs is the surface vapour pressure gradient, while the driving potential in the reverse-osmosis regenerator is the concentration gradient, and the operation of the electrodialysis regenerator is based on the electrochemical potential. The LAMEE is the only indirect-contact technology which can be operated as either a dehumidifier or a regenerator, while other indirect-contact technologies (i.e. reverse-osmosis and electro- dialysis) can only be used as regenerators. Although there is an additional resistant for mass transfer in the LAMEE caused by the membrane, this is believed to be compensated by the lower air-side pressure drop in the LAMEE compared to the packed bed and the elimination of the need for a mist eliminator.

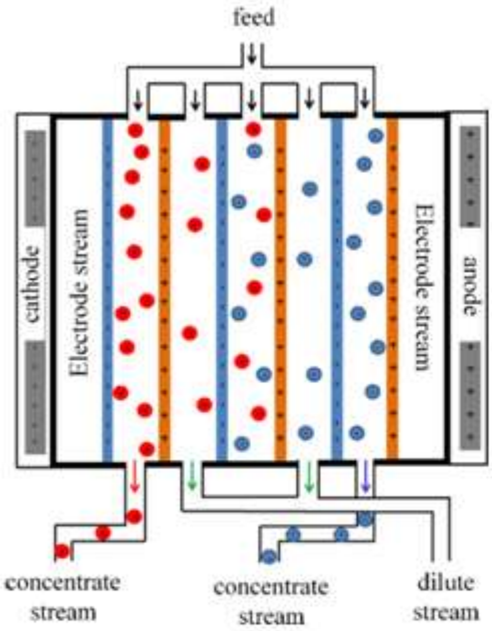


Figure.13. A conceptual schematic for an electrodialysis regenerator.

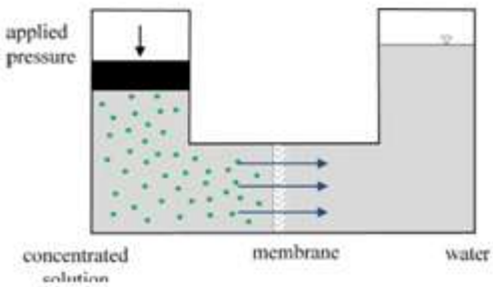


Figure.14. A conceptual schematic for a reverse-osmosis regenerator.

IV. Performance Parameters Of Dehumidifier And Regenerator

The performance indices e.g. cooling capacity and moisture removal rate are commonly used to give an indication about the performance of the system because the dehumidifier and regenerator are among the core components of a LDAC system. In addition, several performance indices are used to evaluate the performance of the whole LDAC system are as follows.

A. Performance parameters of dehumidifier and regenerator

1) Moisture removal rate: The moisture removal rate is the mass of moisture exchange between the air and solution streams per unit time. MRR

$$= \dot{m}_{air}(W_{amb} - W_{air,deh,out})$$

where m is the mass flow rate and W is the humidity ratio
Subscripts air, in and out refer to the air, inlet and outlet, respectively.

2) Cooling capacity: The cooling capacity is the total (i.e. sensible and latent) energy exchange between the air and solution streams. Cooling capacity

$$= \dot{m}_{air}(h_{amb} - h_{air,deh,out})$$

where, h is the enthalpy of the air stream (kJ/kg).
3) Sensible heat ratio: The sensible heat ratio is the ratio between the sensible heat and total heat transfer.
4) Effectiveness: In energy exchangers, sensible effective- ness is the ratio between the actual and maximum rates of sensible heat transfer between the air and desiccant solution streams, latent effectiveness is the ratio between the actual and maximum rates of latent heat transfer, and total effectiveness is the ratio between the actual and maximum rates of total heat transfer. where X is the temperature in the sensible effectiveness and the humidity ratio in the latent effectiveness.
Here it is assumed that the heat capacity rate and mass flow rate of the air are lower than for the solution.
The performance indices (e.g. cooling capacity and moisture removal rate) are commonly used to give an indication about the performance of the system because the dehumidifier and re- generator are among the core components of a LDAC system. In addition, several performance indices are used to evaluate the performance of the whole LDAC system as follows:
5) Coefficient of performance (COP): The COP is the ratio between the cooling capacity and the total primary energy consumption required to operate the LDAC system.
6) Electrical COP: The electrical COP is defined as ratio between the cooling capacity and the electrical energy consumption required to operate the LDAC system.
7) Thermal COP: The thermal COP is defined as ratio be- tween the cooling capacity to the thermal energy consumption in the LDAC system.

B. Applications
Liquid desiccant systems are growing in popularity because of their ability to independently control humidity levels (latent loads) moisture without cooling the air to saturation, the supply air relative humidity falls below 70%. This keeps supply ducts dry and helps avoid mold and bacterial growth. In addition, the scavenging action of liquid desiccant systems could improve indoor air quality by removing airborne contaminants. The various applications of LDS coupled with cooling processes are as follows:

- Comfort air-conditioning in offices, public and residential buildings.
- Warehouses and production halls for preservation and archiving purposes.
- Condensation protection to prevent mold and rust destruction from equipment.

V. Conclusions

Although now limited primarily to industrial applications, LDACs could help solve the most pressing problems now facing the HVAC industry: Peak electric demand created by compressor-based air conditioners. Poor indoor air quality and high indoor humidity that can be difficult to correct with conventional air conditioners. Carbon emissions from the power plants that support electric air conditioners. In HVAC applications, the desiccant must be non volatile. Halide salt solutions are the most commonly used liquid desiccant that meets this requirement. The corrosiveness of halide salt solutions can be managed by working with very low desiccant flow rates in both the regenerator and conditioner. At these low flow rates, the desiccant must be either continually cooled in the conditioner or continually heated in the regenerator to prevent large changes in its temperature. Several researchers have successfully implemented this internal heat exchange by configuring both the conditioner and regenerator as plastic heat exchangers and using the external surfaces of the heat exchangers as the contact media between the desiccant and airflows. The low surface-energy walls of the plastic heat exchangers cannot be easily wetted with desiccant. Thin wicks applied to the walls of the heat exchangers are used The most promising early markets for an LDAC will be those where its exceptional latent cooling and low electrical demand give it a competitive advantage. The demand for sustainable air conditioning is one such market. Solar energy can be effectively applied to air conditioning by using relatively low-cost solar thermal collectors to supply hot water to run an LDAC. By storing cooling as concentrated desiccant, a solar LDAC can operate during the evening and night. This capacity for storage gives LDAC systems an important advantage over a competing solar air-conditioning technology, compressor-based air conditioners powered by solar photovoltaic panels. The compressor-based systems are difficult to implement as solar cooling systems that serve

24-hour loads because of the high cost and inefficiency of storing electric or thermal energy for evening and night hours. Combined heat, power, and cooling (CHPC) applications are a second promising early market for LDACs. In this market, the LDAC would compete with absorption chillers, a mature technology that can run on the low-grade heat recovered from thermally driven power sources. In applications where humidity control is important, the LDAC would have a competitive advantage. The LDAC may also be preferred in CHPC systems in which heat is available at a lower temperature.

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