Desiccant cooling systems: a review

Minaal Sahlot* **and Saffa B. Riffat**
Department of Architecture and Built Environment, University of Nottingham, Nottingham NG7 2RD, UK

Abstract

Desiccant cooling systems have been considered as an efficient method of controlling moisture content in supply air. They do not use any ozone-depleting coolants and consume less energy as compared with the vapour compression systems. This communication provides an extensive review of liquid desiccant systems (LDSs). All the components of an LDS such as dehumidifier, regenerator, packing material and liquid desiccant properties along with its energy storage capabilities have been discussed in detail. In addition, hybrid of LDSs with sensible cooling technologies has been studied. Various types of mathematical models to predict the outlet parameters of the desiccant system and current issues in liquid desiccants have been reviewed in detail. Moreover, solid and other advanced desiccants have also been discussed briefly. Finally, a summary of some successful case studies and economic evaluation of desiccant systems have been given.

Keywords: liquid desiccant; hybrid systems; liquid desiccant issues; dehumidifier and regenerator; desiccant system case studies

*Corresponding author.
minaalsahlot@icloud.com

Received 1 October 2014; revised 24 November 2015; accepted 17 December 2015

1 INTRODUCTION

Research conducted by International Institute of Refrigeration in Paris led to the conclusion that the proportion of energy used by the air-conditioning systems in the household and commercial buildings now accounts for nearly 45%. Air-conditioning systems today account for almost 15% of the total energy consumption of the world [1]. Rising standards of living, technological advancement and increasing population have led to a significant increase in per capita energy demand and thus total energy consumption in the last few decades. Even though human beings have made much progress in almost every field, but still, we rely on fossil fuels as the primary source of energy to meet our demands.

Figure 1, shows the total final energy consumption in India, which was nearly 394 Mtoe. Power sector consumed ∼36% of primary energy. World average was nearly 35% in 2007 in terms of primary energy consumption in power sector. Biomass had the largest proportion of ∼41%, followed by oil of ∼27%. Of the 12% of electricity, energy consumed in residential sector was ∼21%, which is ∼9.93 Mtoe [2].

Figure 2 shows the distribution of electricity in residential and commercial buildings in India. The evaporative coolers used in India are not quite efficient and consume more energy than conventional vapour compression system (VCS). An Estimation made by International Energy Agency showed that, in 2006, ∼22.5 million air cooler were in operation in the residential sector alone [2].

A major proportion of the air-conditioning systems in use are vapour compression-based systems that not only have low efficiency but also use refrigerants like CFC, HCFC and HFC, which are one of the main sources of ozone layer depletion. Other sources of ozone-depleting substances include refrigeration, heat pumps, fire extinguishers and fire protection systems, and solvents. Figure 3 shows the change in atmospheric concentration of chlorofluorocarbons over two decades. CH_3CCl_2 was the only refrigerant whose concentration plummeted starting from 1994 until 2006.

Some coolants like chlorofluorocarbons and hydro chlorofluorocarbons have been in these air-conditioning systems for >60 years [4]. Table 1 shows the average life of coolants, ozone-depleting potential (ODP) and global warming potential (GWP). Ozone-depleting potential is the index that shows the impact of coolant on ozone depletion and is calculated based on R11 or R12 whose ODP is assumed to be one. While GWP is the index

International Journal of Low-Carbon Technologies 2016, 11, 489–505

doi:10.1093/ijlct/ctv032 Advance Access Publication 20 January 2016

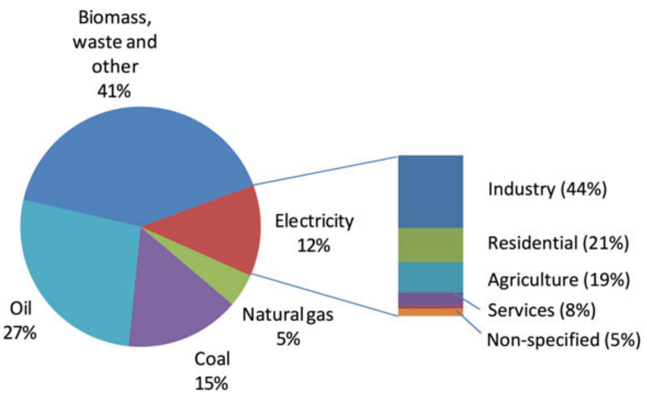


Figure 1. *Total final energy consumption in India in 2007 [2].*

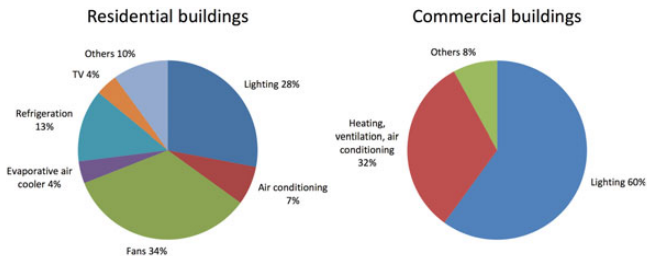
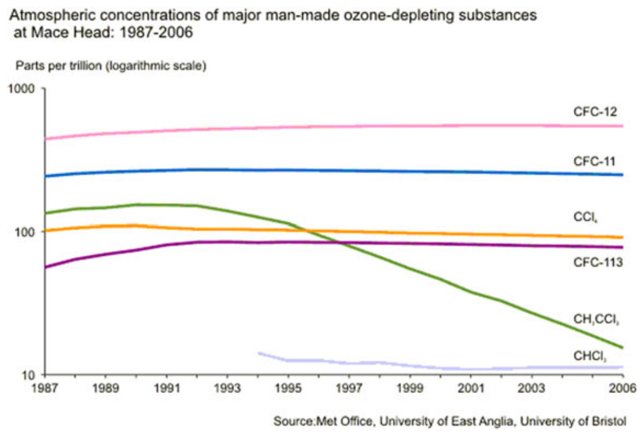


Figure 2. *Electricity usage in commercial and residential building in India [2].*



Source:Met Office, University of East Anglia, University of Bristol

Figure 3. *Atmospheric concentration of ozone-depleting substances [3].*

to determine the greenhouse effect of a coolant and is calculated based on CO_2, whose GWP is equal to one [5]. CFCs have the highest GDP and ODP and their impact on environment lasts between 45 and 1700 years.

These coolants are used to cool the water in the evaporator, as shown in Figure 4. Over the period, they leak into the atmosphere and react with the ozone layer in stratosphere. Leakage leads to the production of more coolant to replace the lost amount; this accounts for ∼65% of the total produced whereas only 35% is manufactured for new air conditioners and refrigerators [7]. Samira and her colleague extensively studied the environmental impact of various refrigerants. They compared the ODP of several chlorofluorocarbons and studied the reaction of chlorine with the ozone layer. They also discussed the idea re-introducing the natural refrigerants as cooling agents [5].

Table 1. *Lifetime, ODP and GWP of refrigerants [5]*

Refrigerant	Life cycle (Years)	ODP	GWP (100 years)
Halons	20 to 70	3 to 10	1300 to 18 000
CFC-11	45	1	3800
CFC-12	100	1	8100
CFC-115	1700	0.6	9300
HCFC	1 to 20	0.05	400 to 1800
HFC	1 to 300	0	140 to 11 700
Ammonia	Few days	0	0

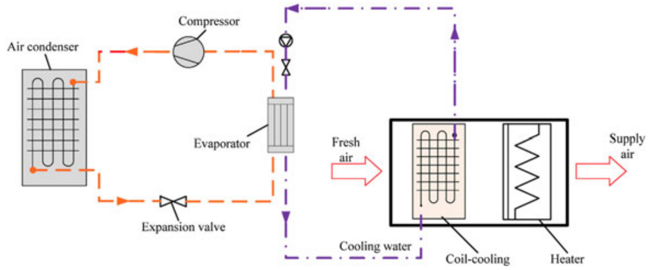


Figure 4. *Schematic diagram of conventional vapour compression air-conditioning system [6].*

The Montreal Protocol (1987) led to some significant changes in the production and consumption of these substances. Since then, initiatives have been taken to reduce the consumption of CFC's and CO_2. Additionally, Under the European Commission Regulation 2037/2000, the use of all HFCs would be prohibited by year 2015 [8]. However, developing countries like India and China still rely on such refrigerants. Environmental issues seem to a take back seat when it comes to luxury and standard of living.

Today, China is one of the largest producers of air-conditioning units whereas India is growing fast in terms of market and manufacturing. Household air conditioners in India today account for 2% and are growing rapidly every year [9]. In his research, Sivak analysed the potential electricity demand for cooling in 50 largest metropolitan areas and its consequence on developing countries. Among these metropolitan areas, nearly 38 of them are in warm climates and 24 out of 38 are in developing countries. Out of theses 24 cities, 7 are in India and 8 are in China. The cooling degree days of these cities are nearly 1.6 times the cooling degree days of warmest areas in advanced cities [10]. Thus, the demand for air-conditioning will only rise in the future and so its consequences on the environment.

Figure 4 shows a vapour compression-based air-conditioning system, which removes moisture from the process air by cooling the air below the dew point with the help of coolants and removing the water vapour by condensation. For instance, to remove the air humidity of ∼7 g/kg of dry air, the air has to be cooled to almost 9°C [7]. As a result, before introducing the cooled air to the space, it is reheated to the required temperature. The process of simultaneous heating and cooling wastes a considerable amount of energy which reduces the performance of the system. Moreover, damp conditions turn into the breeding place for bacteria, which deteriorates the indoor air quality [11].

The main concern of engineers while designing a building is to maintain the balance between thermal comfort, indoor air quality and energy usage. CIBSE defines comfort as 'the condition of mind that expresses satisfaction with the environment'. Air-conditioning systems are designed to maximize human comfort in the interior environment and promise well-being by providing optimum indoor air quality. An operating temperature ranging from 18°C to 26°C and relative humidity ranging from 40–70% is generally acceptable for places with sedentary activity [12]. Additionally, the metabolic activity and clothing also determines the thermal comfort and its consequence on the ventilation. High percentage of water content in the interior space can also give rise to various problems, they are [12]:

(1) Condensation on internal surfaces, which promotes mould growth and thus can be a source of several health problems.
(2) Moisture can also lead to the corrosion of metal, decay of timber and thus, damage the internal structure.

Moisture content or latent heat of air can be controlled either by condensing the water vapour or by using suitable absorbents as used in desiccant cooling systems. While conventional VCSs simultaneously cool and dehumidify the air, a desiccant system only dehumidifies it. Moreover, a desiccant system can be used in combination with evaporative cooling system to maintain the temperature and moisture of incoming air. Earlier, desiccant systems were used for industrial and agricultural sector like textile mills, post-harvest crop storage units for humidity control and drying [13]. However, energy crisis and necessity to develop more eco-friendly systems have led to the introduction of desiccant cooling systems as an effective method to control humidity. Table 2 provides a summary of major differences between the liquid desiccant systems (LDS) and VCSs.

Desiccant systems can use solid desiccants or liquid desiccants. Some commonly used solid desiccants include activated silica gel, titanium silicates, alumina, Zeolite (natural and synthetic), molecular sieves, etc whereas liquid desiccants comprise lithium chloride, lithium bromide, tri-ethylene glycol, calcium chloride and potassium formate. Apart from aforementioned desiccants, there are organic-based desiccants, polymeric desiccants, compound desiccants and composite desiccants. Desiccant systems include rotating desiccant wheel, solid packed tower, liquid spray tower, falling film and multiple vertical bed [14]. Desiccant systems can be categorized based on the type of desiccant used:

(1) Liquid desiccant systems,
(2) Solid desiccant systems,
(3) Advanced desiccants which include polymeric desiccant, composite desiccant, bio-desiccant.

In this review, LDSs have been discussed extensively whereas solid desiccant systems and other types of desiccants have been reviewed briefly.

2 LIQUID DESICCANT SYSTEMS

Figure 5 shows a simple LDS containing a dehumidifier and a regenerator. Moisture from the inlet air is removed in the dehumidification or absorber unit, where the desiccant absorbs the water vapour from the process air. Mass transfer takes place due to the difference in vapour pressure. Subsequently, Heat is liberated during condensation of water and heat exchange due to mixing. After dehumidification, the air is introduced in the space, or in an evaporative cooler to cool down further whereas the diluted desiccant is pumped back to the regenerator.

Before the diluted solution enters the regenerator, it is initially passed through a liquid-liquid sensible heat exchanger and then a heating coil, where its temperature is raised. In the regenerator, the hot diluted solution is exposed to regenerative air, and moisture is transferred from the weak solution to air due to the difference in vapour pressure. This concentrated solution again passes through a liquid–liquid heat exchanger and a cooling coil before it enters the dehumidification unit. Liquid–liquid heat exchanger is used to pre-heat the weak solution and pre-cool the strong solution.

Figure 6 shows the change in vapour pressure of the desiccant solution during the dehumidification and regeneration process. Desiccant solution enters the dehumidifier in State A, when it has high concentration and lower vapour pressure than humid

Table 2. *Comparison between LDS and VCS [13]*

Parameter	VCS	LDS
Indoor air quality	Average	High
Energy source	Electricity, natural gas	Waste heat, solar energy or any low-grade heat
Moisture removal capacity	Average	High
Operational cost	High	Saves 40–50%
Energy storage capacity	Low	High
Solutions	HFC, CFC, HCFC	LiCl, LiBr, HCOOK, TEG
Effect on environment	Harmful	Comparatively eco-friendly

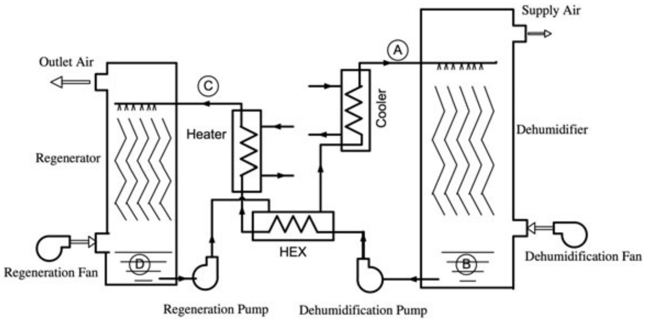


Figure 5. *Schematic of an LDS [15].*

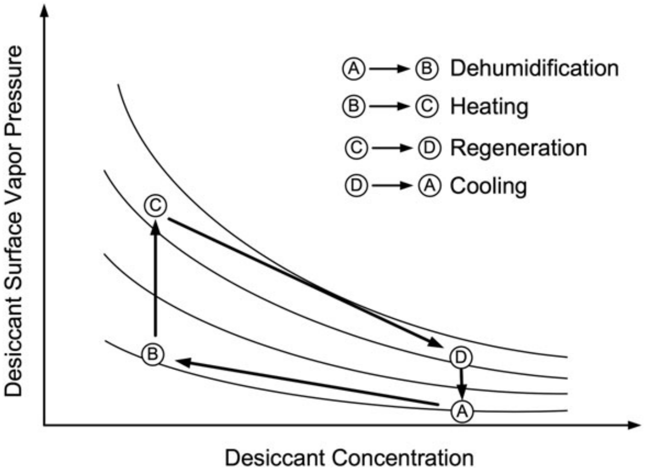


Figure 6. *Vapour pressure change in the desiccant cooling system [15].*

air. During the dehumidification, solution absorbs moisture and reaches State B with lower concentration and higher vapour pressure. Vapour pressure is altered further by heating the solution before it enters the regenerator in State C. At this stage, the vapour pressure of solution is higher than process air, and it transfers the absorbed moisture to the air. Consequently, its vapour pressure reduces and concentration increases and it reaches State D. After that, it is cooled to reduce its vapour pressure further [15].

2.1 Liquid desiccant properties

Liquid desiccant is the most important part of a desiccant cooling system. Its properties such as conductivity, dynamic viscosity, specific heat capacity, density and operating parameters like boiling point elevation, regeneration temperature and energy storage density determine its potential for use as liquid desiccant. Among all the properties, surface vapour pressure is one of the most important parameters that lead to heat and mass transfer in the dehumidifier [13]. Additionally, liquid desiccants are generally odour less, non-toxic, non-flammable and inexpensive. Commonly used liquid desiccants include lithium chloride (LiCl), lithium bromide (LiBr) and calcium chloride ($CaCl_2$). These aqueous salts are more common because they have low vapour pressure. Other examples are tri-ethylene glycol (TEG) and potassium formate (HCOOK). Among the three aqueous salts, the absorption ability of calcium chloride ($CaCl_2$) is least. Nevertheless, calcium chloride is common because it is economical and easily available. On the other hand, lithium chloride has very low vapour pressure and is more stable than other aqueous salts [13].

Liu and his colleagues compared the performance of two commonly used liquid desiccants namely LiCl and LiBr. They also discussed reasons of replacing TEG, one of the earliest liquid desiccants, with other aqueous salts. At standard atmospheric pressure, the difference between the boiling point of water 100°C and TEG 300°C is not very significant as compared with other salts. Thus, there is a high probability of evaporation of TEG during processing. These evaporation losses make it unacceptable for practical use as it can contaminate the air and may affect the health of occupants [16]. Liu and his colleagues also concluded that under similar desiccant volumetric flow rates, lithium chloride (LiCl) dehumidifies air better than lithium bromide (LiBr) as it has lower vapour pressure, while the regeneration performance of lithium bromide is better than lithium chloride. All the aqueous solutions are highly corrosive. Therefore, any carry-over during the dehumidification may adverse effects of the health of the occupants [16].

Potassium formate (HCOOK) is less corrosive as compared with other aqueous salts, has a negative crystallization temperature and is cheaper than other aqueous salts [4]. Potassium formate is a new liquid desiccant and thus, not much research is available currently. Qiu and Riffat investigated a novel air dehumidifier using potassium formate. A highly concentrated solution was used, which effectively dehumidified the air with high moisture content (75% RH), but was rather ineffective at low moisture content (43% RH) [17]. In another investigation conducted by Qiu and colleagues, an evacuated tube was used to regenerate the weak potassium formate. Results indicated that 45°C–50°C was optimum desiccant temperature for solution regeneration, when the mass concentration was between 51.3% and 69.9% by weight [18].

Baniyounes and his colleagues discussed some of the main advantages and disadvantages of liquid desiccants are [14] as follows:

Advantages

(1) Low-pressure drop across the LDSs makes them suitable to use with low regeneration temperatures.
(2) The ability to pump liquid desiccants makes the entire unit small and compact.
(3) Liquid desiccants can be stored and used when heat source is not available. This is advantageous when heat source is not available for regeneration.

Disadvantages

(1) Liquid desiccants like Lithium chloride, lithium bromide and all other salts are corrosive and can damage the desiccant system.
(2) Any carry-over of liquid desiccant along with supply air stream can cause significant harm to the health of the occupants.
(3) In order to handle large volume of liquid desiccant, large pumps are required, which draws a large amount of power.
(4) Desiccants of aqueous salts also face the problem of crystallization.

2.1.1 *Vapour pressure of common desiccants*

Figures 7–9 show the vapour pressure of lithium chloride, lithium bromide and potassium formate at different mass concentration. In dehumidification process, the mass concentration of an aqueous salt is selected, such that vapour pressure of desiccant is less than process air for effective heat and mass transfer. It

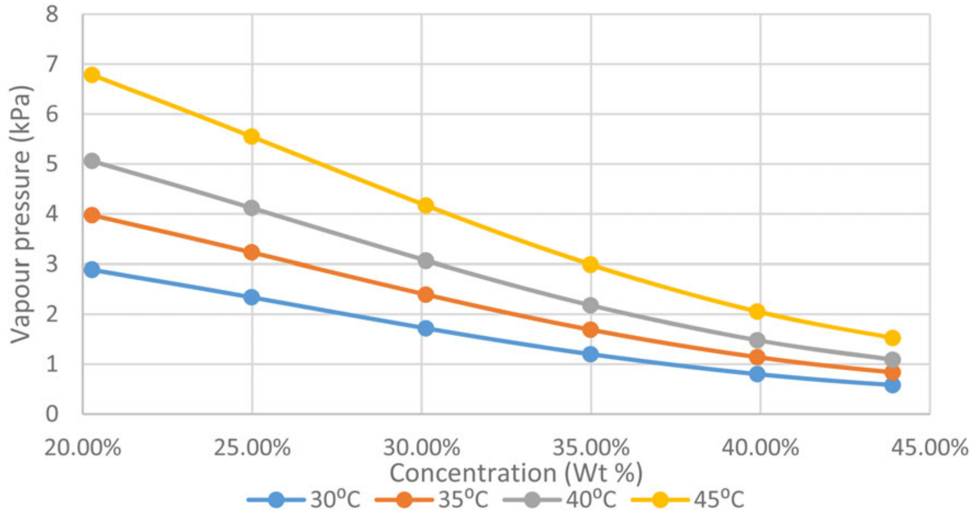


Figure 7. *Vapour pressure of lithium chloride (LiCl) at different mass concentration [19].*

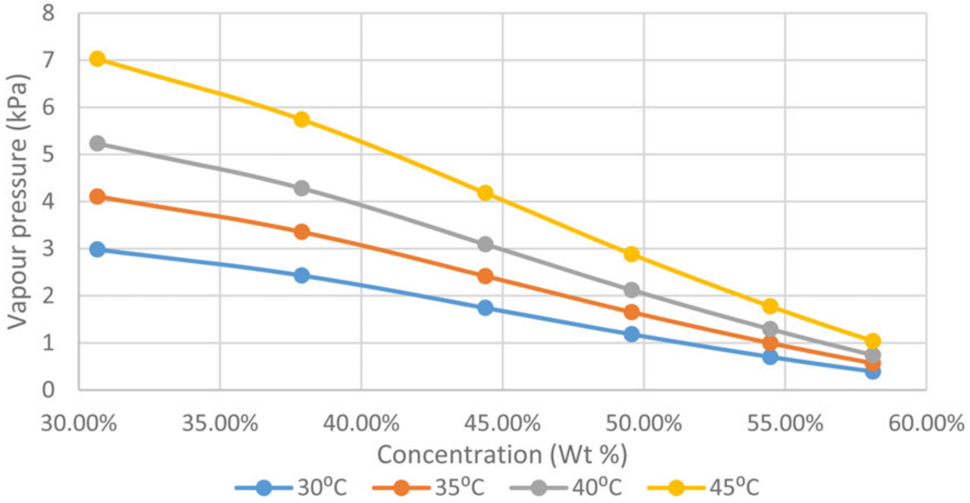


Figure 8. *Vapour pressure of lithium bromide (LiBr) at different mass concentration [19].*

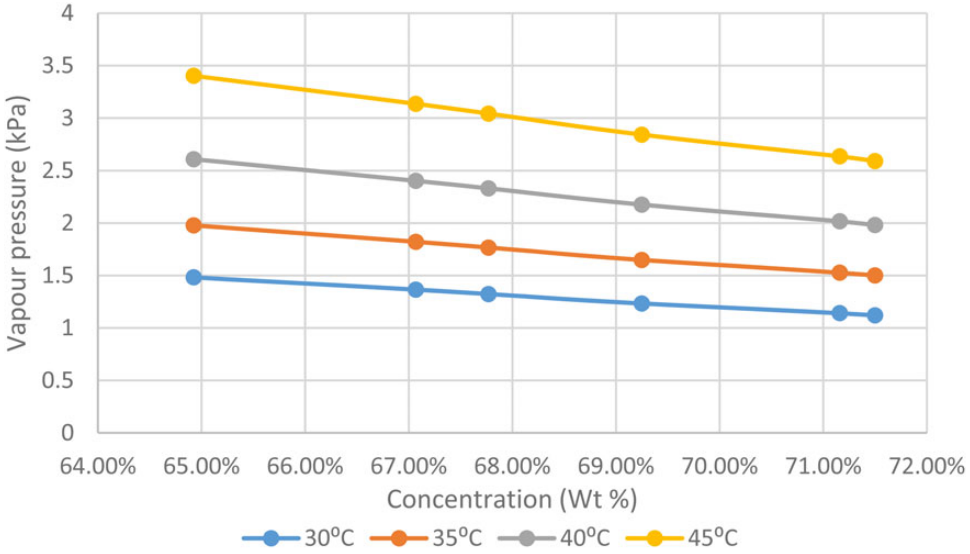


Figure 9. *Vapour pressure of potassium formate (HCOOK) at different mass concentration [20].*

is evident from the figures that the vapour pressure of all the three aqueous salts decreases with the decrease in temperature and increase in concentration. Thus, high concentration is more favourable for dehumidification process.

However, at high concentration, desiccant solution becomes more corrosive and can damage the storage tank and desiccant unit at air outlet. In addition, any carry-over with supply air may affect the environment and health of occupants. Thus, an appropriate concentration is chosen at optimum vapour pressure. For lithium chloride, this ranges between 30% and 36% at temperature between 30°C and 35°C, as vapour pressure is closer to unity. Likewise, for lithium bromide the concentration between 45% and 55% provides vapour pressure closer to unity. For potassium formate, a similar vapour pressure is obtained at 65% to 70%.

2.1.2 *Mixed desiccant*

Mixing two liquid desiccants and studying their properties like vapour pressure, density etc. that affects the dehumidification has been carried out by several researchers. Li and fellow researchers' proposed an innovative method for a mixed-desiccant group, which would be cost-effective. Mathematical form of cost-effectiveness was determined with a combination of desiccant cost and the non-random two-liquid equation, also called NRTL equation [21].

Ahmed and colleague did a thermodynamic analysis of different liquid desiccant. They also tried to develop a new liquid desiccant by mixing two or more salts to obtain the required sorption properties. Lithium chloride and calcium chloride were used in an attempt to produce a mixed solution with lower vapour pressure. A new desiccant solution was formed by mixing some the two salts using appropriate equations. Additionally, they used simple mixing rules to investigate various thermodynamic and physical properties of mixed solutions like viscosity, density and vapour pressure. Comparison with experimental data showed good agreement for density and vapour pressure without the interaction factor [22].

2.2 Dehumidification unit (adiabatic/internally cooled)

The process of heat and mass transfer from the inlet air to liquid desiccant takes place in the dehumidifier, while the temperature difference leads the heat transfer between the air and desiccant solution. Vapour pressure difference drives the mass transfer between air and desiccant. Several theories have been developed to explain the process of mass transfer. Some of them are film theory, penetration theory and surface renewal theory [16]. Commonly used dehumidification units include are finned-tube surface, coil-type absorber, spray tower and packed tower [23]. Dehumidification unit can be classified into two types based on heat extraction process; they are adiabatic dehumidifier and internally cooled dehumidifier.

Figure 10 shows two vertical spray towers with and without internal cooling unit [24]. An adiabatic dehumidifier is a simple unit in which mass transfers from incoming air to the liquid desiccant while heat transfer also takes place due to temperature difference and latent heat of condensation of water vapour. Heat discharge reduces the efficiency of dehumidification. One solution to control the temperature in dehumidifier is to increase the flow rate. However, higher flow rates increase the possibility of carry-over. Moreover, higher flow rates in dehumidifier are followed by higher flow rates in regenerator, which reduces the thermal coefficient of performance of the system [24].

Another solution is to replace the adiabatic dehumidifier by internally cooled dehumidifier. This type of dehumidifier consists of an embedded cooling coil that provides cold water or air, to remove the heat produced during the dehumidification process. Cooling unit controls the temperature of the desiccant and air thereby improving the efficiency of the system. Moreover, the main advantage of cooing coil is that it allows for lower flow rates, which improves the performance and reduces the chance of carry-over.

2.3 Two-stage dehumidification unit

Xiong and his colleagues developed a two-stage liquid desiccant cooling system using an exergy analysis. In this type of dehumidification process, process air has to pass through two-dehumidification units. Inlet air is passed through calcium chloride solution followed by a lithium chloride solution as shown in Figure 11. The main advantage of pre-dehumidification process using calcium chloride is that it helps in reducing irreversibility in the dehumidification process. On the other hand, during regeneration lithium chloride is regenerated first followed by calcium chloride. It is because regeneration ability of calcium chloride is higher than that of lithium chloride. Results showed that the thermal coefficient performance of the proposed system was 0.73 whereas exergy efficiency was 23%. Additionally, the energy storage

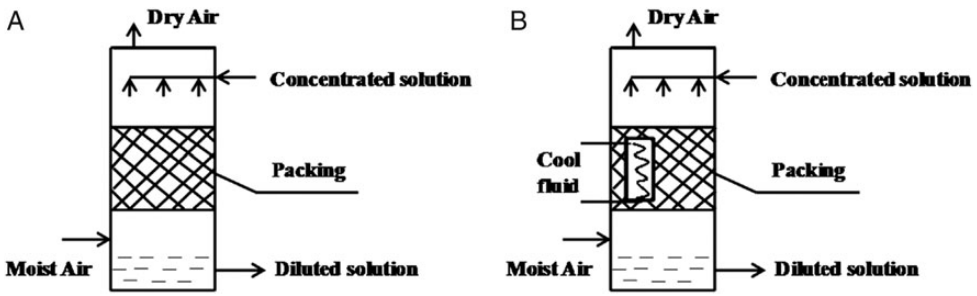


Figure 10. *(A) Adiabatic dehumidifier, (B) internally cooled dehumidifier [24].*

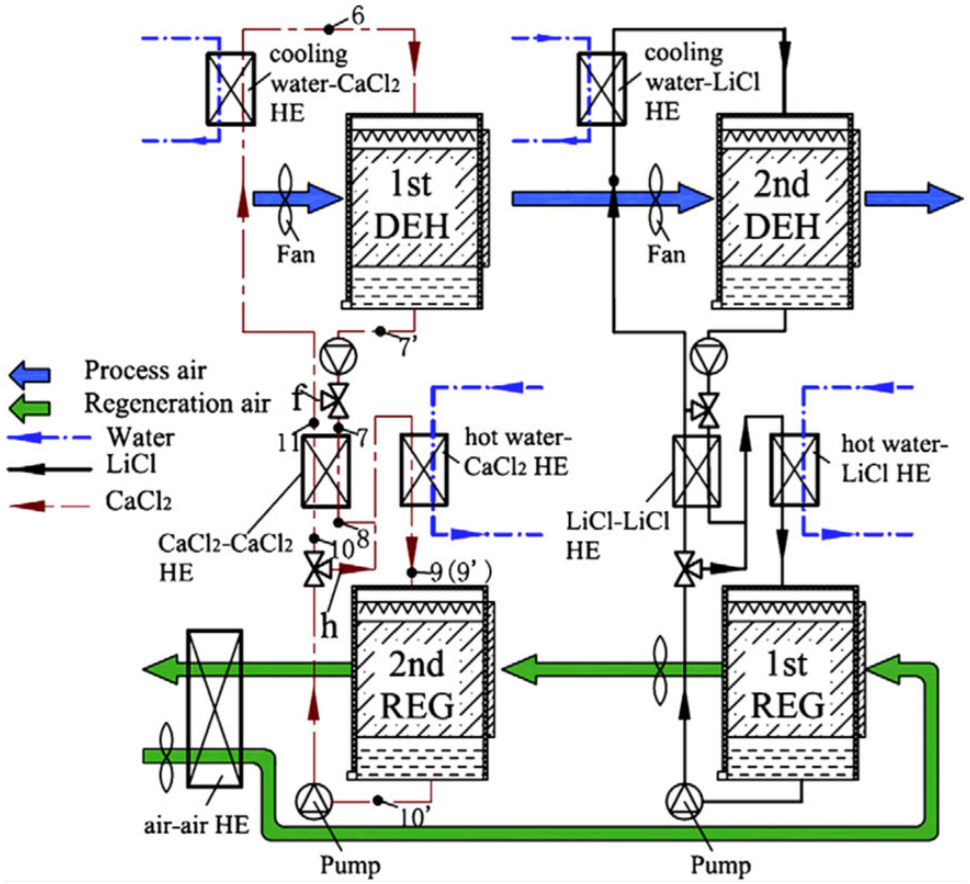


Figure 11. *Two-stage dehumidification unit [25].*

capacity of the desiccant solutions showed considerable improvement over single-stage dehumidification [25].

In yet another investigation conducted by Xiong and his fellow researchers, calcium chloride was used for pre-dehumidification followed by another dehumidification using lithium bromide. In this case, an evaporative cooler was placed between the two-dehumidification processes. Evaporative cooler not only reduced the heat of mixing but also reduced the temperature of process air by 3°C. Results indicated that the thermal coefficient of performance was 0.94 and coefficient of performance of the whole system was 2.13. The storage capacity of lithium bromide and calcium chloride was improved by 26 and 30 times respectively as compared with single-stage system [26].

Table 3. *Observations of various dehumidifier packing material*

Packing Material	Observation	Reference
PP, PVDF and Tyvek Membrane	Reduces carry-over but achieves Low dehumidifier effectiveness	[28]
Munters Celdek with silica gel	High dehumidification capacity	[21]
Structured packing (corrugated angle 60°, void ratio 0.88)	Higher WCR and effectiveness	[29]
Random packing	Uneven distribution of desiccant	[27]

2.4 Dehumidifier core packing material

A packing material is a medium for liquid desiccant to interact with the process air stream to extract moisture. A packing material must be inert to liquid desiccants. Packing materials and their configuration significantly influence the performance of dehumidification unit of the desiccant cooling system. They are broadly classified as regular/ structured packing and random packing based on their configuration. Regular packing increases the performance of the dehumidifier by providing low-pressure drop for the air stream and is easy to install as compared with random packing. It also reduces the liquid desiccant resistance in the dehumidification unit. On the other hand, random packing material cannot adjust to the variation in liquid desiccant flows and results in uneven distribution of the desiccant solution over the surface of the packing material, which reduces the performance of the dehumidification system. However, regular packing is costlier than random packing [13, 27].

Some common examples of random packing material include ceramic, plastic, polypropylene pall whereas structured packing material are either gauze type or sheet type. Structured packing materials are generally made of stainless steel-corrugated orifice plate, celdek, etc. [24].

Table 3 shows a summary of observations from various researches. Bassuoni carried out an experimental study on the performance of structured packing cross-flow desiccant system using calcium chloride as liquid desiccant. His observations led to the conclusion that the water condensation rate and effectiveness of both regenerator and dehumidifier increases with the increase in structured packing thickness [29].

Void ratio and packing thickness are important parameters. Airflow resistance depends on void ratio, which decreases with the increase in void ratio [13]. Qi and his colleagues investigated the factors that influence the wetted area and film thickness of the falling film liquid desiccant. Based on experiments, they concluded that increase in wetted area improves mass transfer performance, while film thickness has a negative effect [30].

Li and other researchers' compared various dehumidification units and gave some valuable recommendations to modify the dehumidifier design. In one dehumidification unit, structured corrugated packing of Munters Celdek was combined to silica gel. Experiments using this desiccant core showed that there was an improvement in dehumidification capacity of liquid desiccant. Their work also showed the importance of surface roughness of dehumidifier core and led to the conclusion that rougher surface would perform better than smoother one and the chance of any reverse dehumidification reduces considerably [21].

2.5 Flow patterns

Figure 12 shows the flow patterns of the humid air and liquid desiccant. There are three common flow patterns in an adiabatic dehumidifier namely parallel flow, cross-flow and counter flow. Flow patterns determine the contact area and the process of interaction between desiccant and inlet air. Flow patterns also determine the type of mathematical model that is suitable for a particular desiccant system. Liu and his colleagues prepared analytical solutions of dehumidifier and regenerator based on the type of flow using mathematical models from existing research. Analytical solutions of all the cases are in good agreement with the experimental results from other researches [32].

Liu and his colleagues performed an analysis on an internally cooled dehumidifier and concluded that the performance of counter flow is best followed by cross-flow, while the performance of parallel flow is not optimum [31]. Mohammad and his colleagues studied the effect of mass flow rate on the performance of cross-flow. They used MATLAB to perform simulations and concluded that water condensation rate and dehumidifier effectiveness increases with the increase in flow rate up to a certain level, after which it drops [33].

2.6 Regenerator unit

A regenerator is a unit that is used to convert the weak or diluted desiccant solution into concentrated solution as shown in Figure 5. Regenerator is similar to the dehumidifier, however, the basic function and process of the two units is opposite to each other. Another difference is that a dehumidifier unit has a superfluous layer of insulation to reduce the heat and mass transfer from the atmosphere.

Generally, desiccant solution is pre-heated before introducing into the regenerator. Water vapour is transferred from hot desiccant solution to incoming air at normal temperature. However, some desiccant regenerators also use pre-heated air to regenerate the liquid desiccant. This is more common in solid desiccant regeneration units rather than liquid desiccant regenerators. One example is the regeneration process adopted by Alosaimy and Ahmed in their research. They investigated the performance of the solar water heater used for pre-heating regeneration air using an air–water heat exchanger. A honeycomb packing was used to regenerate calcium chloride solution. Results indicated that an air–water heat exchanger could effectively regenerate the liquid desiccant (calcium chloride in this case) from 30% to 50% [34].

2.6.1 *Internally heated regenerator*

Regenerator is usually an adiabatic unit. However, Yin and his colleagues showed that as the regeneration process continues the temperature of liquid desiccant reduces and solution cannot provide latent heat of vaporization required to transfer water present in the solution to the incoming air. Thus, the performance of the system reduces. Therefore, they proposed an internally heated regenerator in which a heating coil provides heat energy to maintain the solution temperature [35].

Regeneration process using thermal energy is the most common method. However, there are some other methods for regeneration as shown in Figure 13. They are as follows:

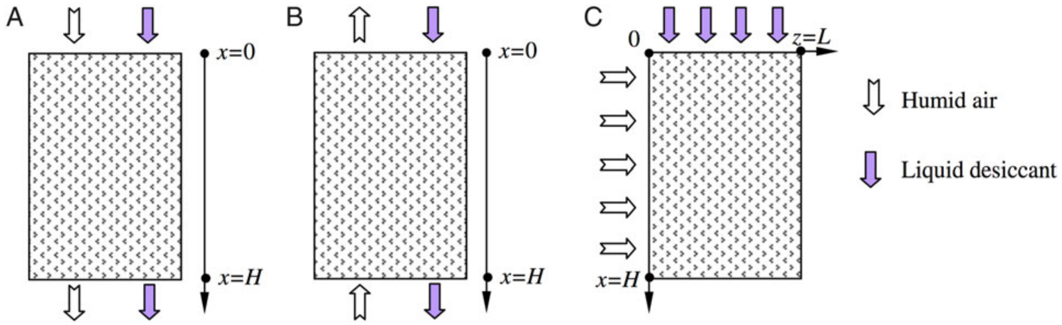


Figure 12. *Flow patterns of air and liquid desiccant in dehumidification unit [31].*

2.6.2 *Electro dialysis regeneration*

Cheng and his fellow researchers experimentally investigated the performance of an electro dialysis regenerator for liquid desiccant. In electro dialysis process, ions are transported through a selective membrane under the effect of electric field. A parametric analysis of electro dialysis regenerator was performed based on current utilization and solution mass transfer rate per unit area of anion exchange membrane. Results showed that maximum current utilized by the system was 55%. Additionally, increase in desiccant flow rate increases the mass flow rate and current utilization by strong solution [36].

2.6.3 *Regeneration by reverse osmosis*

Reverse osmosis is commonly used for desalination of seawater. Similarly, weak solution can be converted into a strong solution by removing the added water from the desiccant [37]. In this process, an MFI zeolite membrane was used by Al-Sulaiman and his colleagues to separate the weak calcium chloride solution from the water. They proposed this method for countries like Saudi Arabia where there is a scarcity of soft water. They combined this method of regeneration with a two-stage evaporative cooling in which water needed by the evaporative coolers was supplied by the reverse osmosis [37].

2.7 Energy source

Desiccant cooling systems require electricity to operate pumps and fans and heat energy to pre-heat the desiccant solution for regeneration. As the desiccant system can operate on low heat, heat energy can be provided through solar thermal systems or any waste heat source from chimneys, power plants, etc.

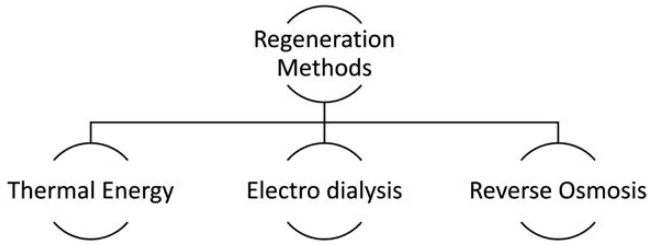


Figure 13. *Various methods of regeneration.*

Solar energy can be harnessed in two ways. First, a PV system in which solar energy is used in the form of electricity to drive the pumps and fans. Second, heat energy form the sun can be harnessed to regenerate the weak desiccant solution [8]. Figure 14 shows the schematic diagram of a desiccant cooling system integrated with an evaporative cooler and a solar collector. Combined solar collector and regenerator is used directly to pre-heat the desiccant solution before introducing in the regenerator. Another type of solar collector uses water as a medium of heat transfer between collector and liquid desiccant. Former type of solar collector device is more efficient as all the heat energy absorbed by the collector is directly transferred to the desiccant solution. However, as desiccant solution is corrosive in nature, the solar collector has to be designed to be corrosion resistant. Katejanekarn and his colleagues used a solar regenerated LDS and compared results to model literature. They concluded that the relative humidity of inlet air was reduced by 11.1% [39].

Energy can also be obtained from several other sources, like waste heat from a combined heat and power plant. Riffat and Jradi investigated into the configuration and operation strategies of a tri-generation system. A tri-generation system is a combined heating, cooling and power system. This system can operate using gas turbine, internal combustion unit. While heating can be provided from the waste energy, it can also be used to operate a desiccant cooling system [40]. Figure 15 shows a combined heating, cooling and power system in which a biomass gasification unit produces gas which is introduced into an internal combustion engine to produce electricity. Waste heat recovered from the system is used for heating and cooling in an absorption cooling unit [40].

2.8 Energy storage

Desiccant cooling systems operate on low-grade heat, which can be obtained from various sources. However, interim unavailability of such sources can impede the operation of desiccant systems or they would have to rely on electricity or other auxiliary heating devices for their operation. A solution to this problem is

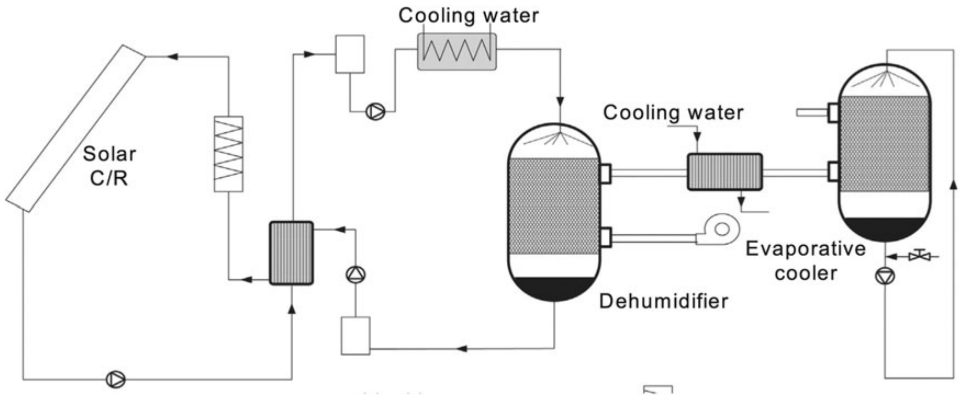


Figure 14. *Solar powered desiccant cooling system [38].*

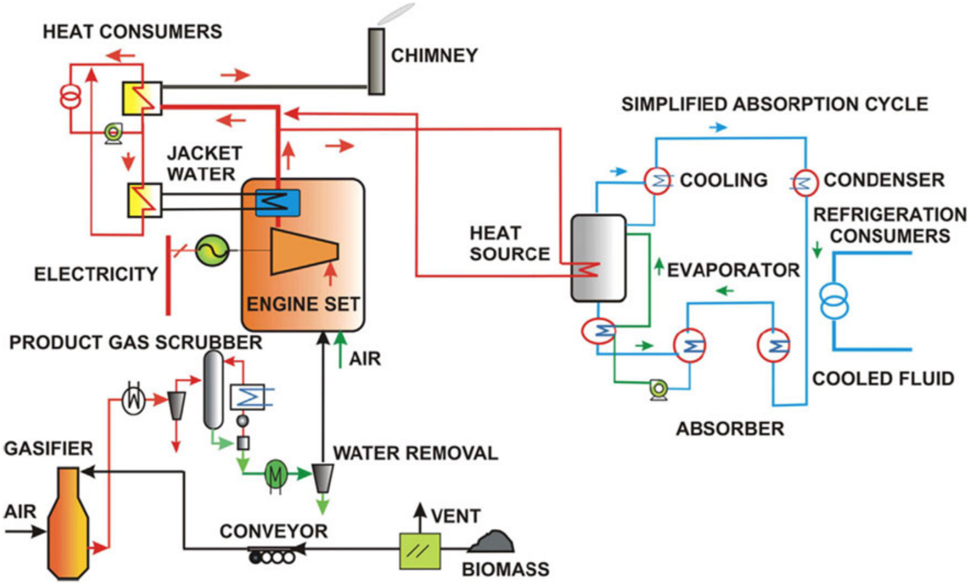


Figure 15. *An internal combustion-based tri-generation system with a biomass gasification unit [40].*

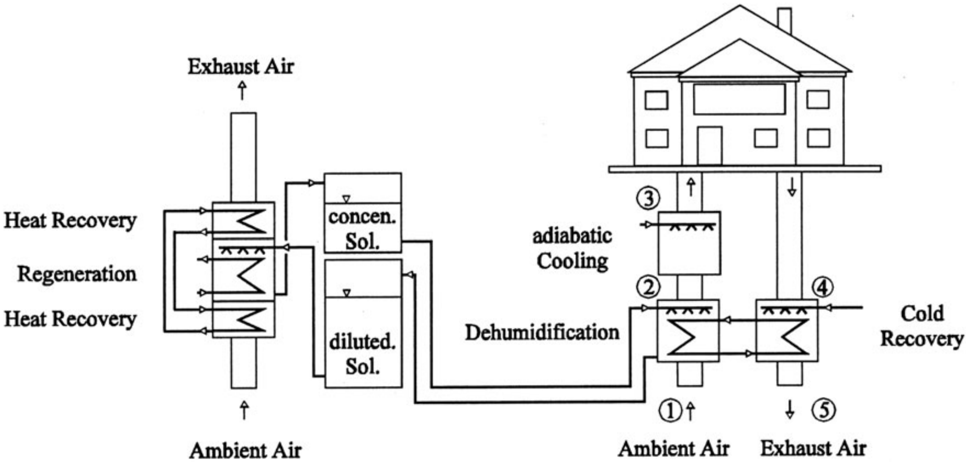


Figure 16. *Liquid desiccant system with energy storage [42].*

to store the thermal energy in the form of regenerated desiccant solution and use it for dehumidification when thermal energy is not available. Research has shown that the energy storage ability of liquid desiccants like lithium chloride and calcium chloride is ∼3.5 times that of solid desiccants like silica gel and zeolites [41].

Kessling and his colleague developed new dehumidifiers and performed experiments to study the relationship between dehumidification enthalpy storage and various impacting factors in a cooled absorber [41]. Figure 16, shows an LDS designed to store energy in the form of regenerated desiccant solution. Here, the dehumidified air is cooled with the help of an evaporative cooler. A heat exchanger has been added to cool the air during the dehumidification process by recovering cold from exhaust air. Weak desiccant solution is stored in a storage tank. It is regenerated using a hot water heat exchanger and strong solution is stored in another tank. Thus, thermal energy is stored in the form strong solution, which can be used for dehumidification when low-grade heat is not available for regeneration [42].

3 HYBRID LIQUID DESICCANT AIR-CONDITIONING SYSTEMS

Liquid desiccant systems are suitable for extracting latent heat from the air. However, a desiccant cooling system is incapable of removing sensible heat from the air. Therefore, desiccant systems are often used in combination with direct or indirect evaporative cooling system, vapour compression refrigeration system or vapour absorption system to remove latent and sensible heat before introducing into the space. A brief review of the systems shown in Figure 17 is as follows:

3.1 Liquid desiccant combined with evaporative cooling system

Figure 18 shows a desiccant cooling system combined with an evaporative system used by Yin and his colleagues to perform an experimental study on the dehumidifier and regenerator. The system has three major components namely dehumidifier, regenerator and an evaporative cooler. Air after being dehumidified goes to the evaporative cooling unit, where the sensible heat is removed and introduced into the interior space while the diluted desiccant solution goes to the regenerator unit for regeneration. A storage tank is also provided, which can store the regenerated desiccant solution to be used when low-grade heat is not available. They used packed tower structure for both the dehumidifier and regenerator.

Kim and his colleagues investigated an LDS integrated with an evaporative cooling assisted 100% outdoor air system. They investigated the energy saving potential of the system and compared it with a conventional variable air volume system. TRNSYS 16 was used for simulation and results concluded that the hybrid consumes 51% less cooling energy compared with VAV system [44].

3.2 Liquid desiccant system combined with VCS

Vapour compression systems are the most common systems for sensible cooling. They have been in operation for more than two decades now. Most of these systems are advanced and require less energy than their predecessors require. An LDS integrated with a VCS can be highly efficient in space cooling. Henning and his fellow researchers studied the potential of solar energy use in desiccant cooling systems and concluded that desiccant system combined with conventional system can save up to 50% of primary energy [45].

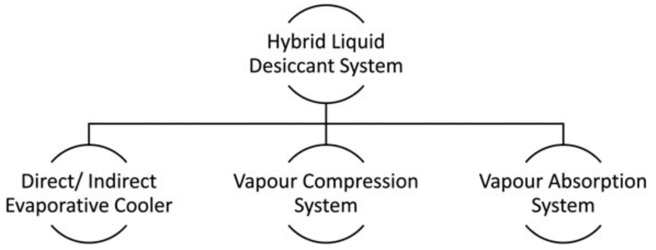


Figure 17. *Hybrid of LDS with various systems.*

Khalil investigated the potential of one such system, which is called hybrid-desiccant-assisted air conditioner. The COP of the system tested was 3.8. Total cooling capacity of the system was 6.15 kW, using 2.6 kW VCS. He used lithium chloride as liquid desiccant. Figure 19 shows the schematic diagram of hybrid system proposed by Kahil. Strong solution from the tank is pumped and sprayed uniformly over the evaporator surface area. Process air to be dehumidified is passed through the evaporator in the cross-flow direction. The evaporator and desiccant helps in simultaneously cooling and dehumidifying the process air while the diluted desiccant solution is collected in the weak solution tank. After that, the diluted solution is pumped to absorb heat from the heat exchanger that uses the waste heat rejected from the condenser of the VCS to pre-heat the diluted solution. A heating coil in the regenerator tank provides the additional heat required by the solution to completely. The proposed system can attain yearly energy savings of ∼53% compared with a VCS with a reheat mechanism [46].

A novel design of a hybrid system of VCS and LDS was proposed by She and Colleagues. In this system, liquid desiccant cooling system along with an indirect evaporative cooler was used to sub-cool the refrigerant of the liquid desiccant cooling cycle. Moreover, the desiccant solution was regenerated using the condensing heat of the VCS. Results obtained from the thermodynamic analysis showed that the proposed system attained higher coefficient of performance than conventional system as well as the reverse Carnot cycle under similar working conditions. About 18.6% and 16.3% higher COP was achieved using hot air and ambient air, respectively [47].

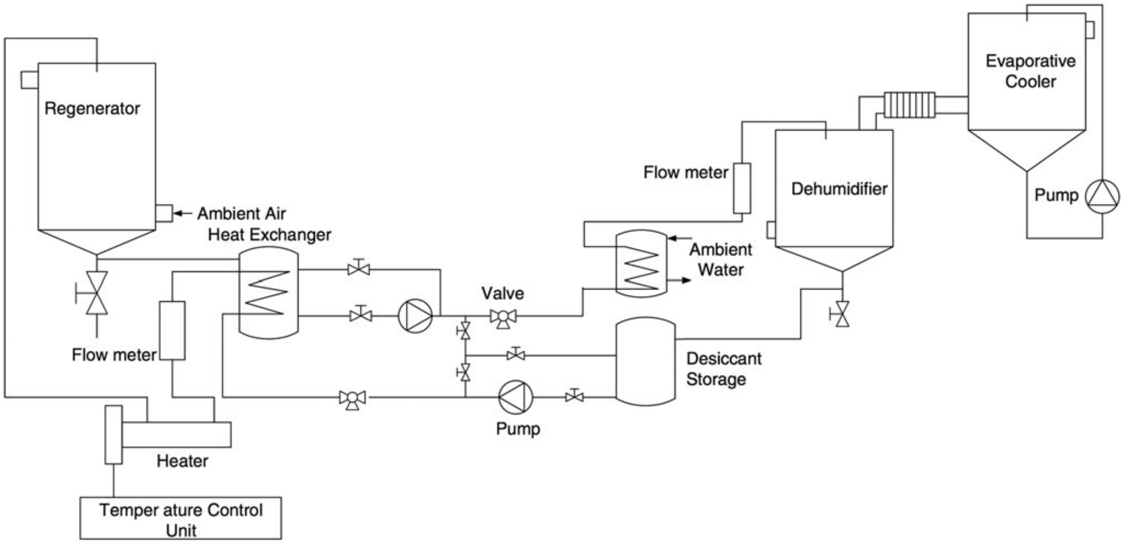


Figure 18. *A desiccant cooling system combined to an evaporative cooler [43].*

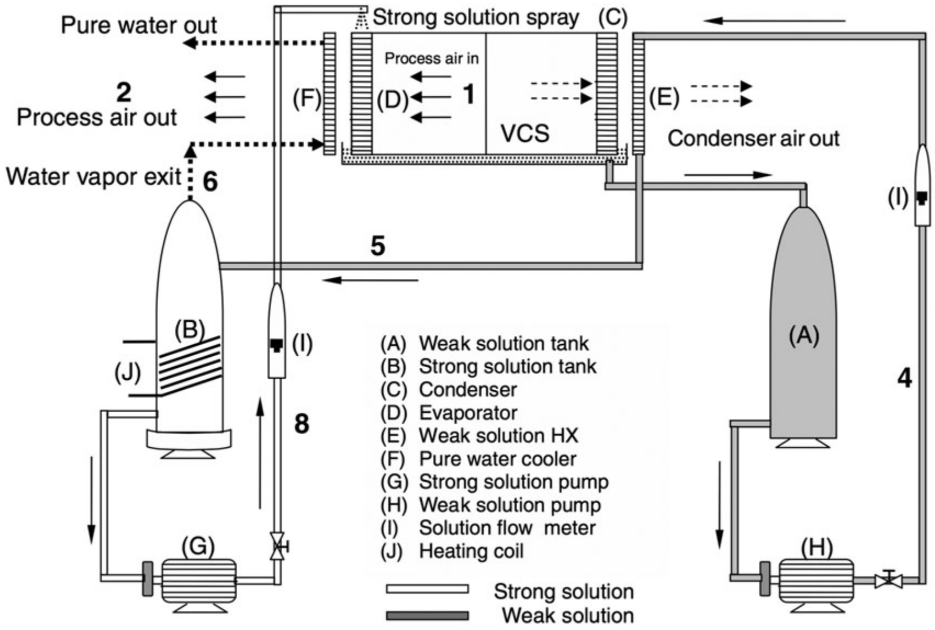


Figure 19. *A schematic of hybrid desiccant-assisted air conditioner [46].*

3.3 Liquid desiccant-based vapour absorption system

Pang and his colleagues categorized absorption and adsorption system based on heat source and its application [48]. The main function of both these systems is to refrigerate and dehumidify. Sarbu and his colleague differentiated the two systems by their phenomenon. Absorption is a volumetric phenomenon, while adsorption is a surface phenomenon [8]. A hybrid liquid desiccant-based air-conditioning system with a vapour absorption system was proposed by Ahmed and his colleagues. The hybrid is an open cycle system and used lithium bromide for both absorption and dehumidification. The simulation study showed that COP of the proposed hybrid system ranges from 0.96 to 1.25 and is 50% higher than the conventional vapour absorption system. In addition, they concluded that lower water temperature and moisture content would improve the performance further [7].

4 MATHEMATICAL MODELS OF LDSs

A mathematical model is a set of equations to determine the unknown parameters based on known variables. Models can be very accurate but complex at the same time. On the other, they can be simple, but not so accurate. A model that is simple and accurate at the same time is considered as the most appropriate model [49].

Luo and his colleagues reviewed some common mathematical models for predicting heat and mass transfer process in the liquid desiccant dehumidifier. They categorised the models based on the type of dehumidification unit, adiabatic or internally cooled dehumidifier. For an adiabatic dehumidifier finite difference model, effectiveness-NTU model and simple model are the three commonly used mathematical models [27]. Table 4 provides a list of various types of model:

Table 4. *Summary of mathematical models*

Type of model	Flow	Reference
Effectiveness NTU model	Counter flow	[73]
Simple/quick prediction	Counter flow	[57]
Empirical correlations	Cross-flow	[56]
Artificial neural network	Counter flow	[59]
Kinetic mass transfer model	Cross-flow	[61]
Simple hybrid model	Counter flow	[15]
Model based on Runge-Kutta fixed step method	Counter flow	[55]
Simple analytical	Cross-flow	[54]

Bassuoni developed an analytical method using engineering equations solver to estimate all exit parameters of a cross-flow air dehumidifier using $CaCl_2$ as liquid desiccant. Deviation between the analytical solution and experimental results ranged between −5.65% and +6.63% in terms water condensation rate [54].

Koronaki and his fellow researchers developed a heat and mass transfer theoretical model based on Runge-Kutta method to study several parameters including gradients of air, humidity ratio, desiccant temperature and desiccant flow rate and indicated the parameters that affect dehumidification process. Results obtained from the model showed maximum discrepancies of ±2.9%, ±15.9%, ±2.8% in air outlet temperature, air humidity ratio at outlet and solution temperature, respectively [55].

Liu and others proposed a simple model based on empirical correlations of enthalpy and moisture effectiveness to predict the performance of dehumidifier. The difference between the predicted and experimental results of a cross-flow packed dehumidifier 6.3%

and 6.0% for enthalpy effectiveness and moisture effectiveness, respectively [56].

Gandhidasan gave two simple models: one for air dehumidification and another for desiccant regeneration. Both the models were proposed for liquid desiccant in a packed bed flowing in a counter flow direction. He defined dimensionless parameters for both the models: one based on moisture difference and another one based on vapour pressure difference. Both the models were compared with previous researches and showed very good agreement with the experimental results [57, 58].

Gandhidasan and Mohandes gave an artificial neural network model and analysed on dehumidification unit for random packing using lithium chloride [59]. Another such model was given by Parmar and Hindoliya. They based their model on desiccant wheel. Both the models were in good agreement with their respective experimental data [60].

Reverse dehumidification is one of the major problems of desiccant. When it occurs, mathematical models fail to predict the results. Li and his colleague developed a new model based on molecular kinetic theory of gas. Model worked well with experimental data and predicted reverse dehumidification [61].

5 CURRENT ISSUES IN LDSs

Although desiccant systems have proven to be more efficient and environmentally friendly than conventional VCSs, desiccant systems have some drawbacks and problems. Solving these problems would make them more competitive in the market. Major problems involve reverse dehumidification, desiccant unit corrosion, desiccant carry-over. Additionally, conventional air conditioners come in compact sizes. But, the desiccant systems combined with an evaporative cooler are usually bulky [13]. Research has shown some considerable solutions. Reverse dehumidification occurs when process air is humidified instead of dehumidification. Reverse dehumidification can occur even when the vapour pressure of liquid desiccant is positive [61]. The problem of corrosion is solved by using plastic material in the dehumidification unit and the storage tank.

Carry-over occurs when particles of desiccant solution mix with the process air. In indoor spaces, carry-over can be harmful for the health of occupants and can lead to the corrosion of ducts and pipes near air outlet. One solution to this problem is to introduce micro-porous membrane. Allowing moisture transfer though these semipermeable membranes would prevent interaction between the process air and liquid desiccant [62]. Additionally, it also provides a distinct and constant surface area which would be free of air and desiccant flow rates and would inhibit the advance of microbes in the working conditions due to low moisture content on membrane-air interface [62, 63].

Das and Jain did an experimental investigation using microporous semipermeable hydrophilic membranes as desiccant cores to reduce the carry-over of liquid desiccant in supply air. Lithium chloride was used as a liquid desiccant to test membrane contractors developed from hydrophobic PP, PVDF and Tyvek membranes. The results indicated that although the problem of carry-over was controlled, dehumidification effectiveness was low varying between 23% and 45%, as membranes create additional resistance [28].

Kumar and his colleagues proposed a simulation and parametric study of two innovative individual liquid desiccant cycles. Both the cycles used multiple absorbers based on falling film design. Falling film-based absorber was chosen as it has low-pressure drops. Proposed cycles not only improved the coefficient of performance of the system but also controlled the problem of carry-over when operated at higher concentration of desiccant solution [64].

Another problem is the crystallization of liquid desiccant. Crystallization can occur in a liquid desiccant solution stored at high concentration with decrease in temperature [13]. Ge and his colleagues did a comparison study between experimental data and; heat and mass transfer model for membrane-based dehumidifier and regenerator. The results showed that the predicted results from the model agreed with the experimental results of the dehumidifier. However, the model did not hold agreement with the regenerator experiment results. Discrepancies between the model and experimental data were caused by the crystallization of lithium chloride aqueous solution in the openings of membrane during the regeneration process. These crystals reduced the moisture transfer and consequently produced errors in experimental data [65].

6 A BRIEF REVIEW ON SOLID AND OTHER DESICCANTS

6.1 Solid desiccants

A solid desiccant system commonly uses a solid desiccant embedded in a desiccant wheel or a cross-flow wheel. Solid desiccants are inexpensive, non-flammable, non-corrosive and environmentally friendly. They do not react chemically with moisture of the process air [14].

The drying capability of solid desiccants is higher than liquid desiccants. They can be cleaned easily. However, they require relatively higher regeneration temperature [14]. Figure 20 shows a desiccant wheel used for dehumidification of process air and regeneration of solid desiccant. Unlike liquid desiccants, the dehumidification and regeneration process in the solid desiccant is always simultaneous. Desiccant wheel is divided into two parts with the help

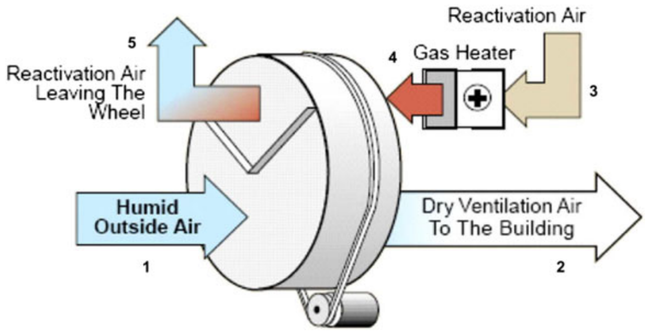


Figure 20. *Schematic of solid desiccant wheel [23].*

of a stunt. In one part, the humid air passes through the desiccant wheel for dehumidification. In another part, hot air is passed to remove the added water from the solid desiccant.

The performance efficiency of solid desiccants has significantly improved in the recent years. Liang researched on a refrigeration dehumidification system with membrane-based total heat recovery and showed that coefficient of performance is 2 to 3 times higher than conventional refrigeration dehumidification system [66]. Zhao and others led an experimental investigation on a desiccant dehumidification unit using fin-tube heat exchanger with silica gel coating and found that the unit can be independently used as a dehumidifier with 100% fresh air under mild conditions [67]. Mintova and others investigated on nano-porous materials with enhanced hydrophobicity and high water sorption capacity. They investigated parameters like mechanism of adsorption, ability of modification, enhancement of water adsorption capacity, regeneration ability and stability. Inorganic materials like zeolites, clay and silica were studied [68].

Goldsworthy and White performed simulations using two dimensional numerical model to determine the limiting performance mechanisms in dehumidification process of desiccant wheel. They studied the influence of desiccant equilibrium adsorption isotherm on the overall performance of wheel. Parameters like heat of adsorption, moisture diffusion rate, desiccant specific heat capacity and density were used to provide a further understanding of the restraining mechanisms for low regeneration performance. They concluded that exothermic adsorption process and heat carry-over from the regeneration stream limited the dehumidification process [69].

6.2 Other advanced desiccants

Both solid and liquid desiccant have several disadvantages. For instance, the adsorption capacity of silica gel is low and requires high regeneration temperature. Desiccants containing salts of chloride like lithium chloride and calcium chloride may give rise to corrosion problem. In addition, zeolites have low water capacities and a higher cost of regeneration. An intensive research is going on to develop new desiccants with a higher performance. New and advanced desiccant that have been developed with suitable modification in the properties of conventional desiccant like bio-desiccant, composite desiccant and polymeric desiccant has the capability to overcome the limitations of conventional desiccants [70].

Jia and colleague used a compound desiccant to develop high performance desiccant cooling system and concluded that under practical operation a compound desiccant can improve the overall performance of a desiccant wheel by 20–30% over desiccant wheel with silica gel. Tests showed that the coefficient of performance of system may reach 1.28, which is ∼35% more than the desiccant wheel with only silica gel [71].

Lee and Lee investigated into a novel polymeric desiccant and found that sorption capacity of super polymer desiccant is 2–3 times higher than silica gel [70]. Guo and his colleagues investigated micro-porous coordination polymers (MCP) and compared capacity and efficiency with activated alumina and concluded that polymeric desiccants hold potential of commercial use. However, further research on various parameters of advanced desiccants is yet to be conducted to study behaviour of MCP in extended cycles before coming to an actual conclusion [72].

7 A BRIEF ON CASE STUDIES AND ECONOMIC EVALUATION

Desiccant cooling systems combined with other sensible cooling technologies have started establishing its way into the market. Countries that have hot and humid climate have started replacing the conventional systems with more efficient and environmentally friendly solutions. A brief about some successful case studies along with a summary of economic evaluation done by various researches is discussed in this section. Table 5 shows the outcomes of various case studies

7.1 Case studies

Baniyuones and his colleagues accessed a solar powered desiccant cooling system installed at the Rockhampton campus of Central Queensland University, Australia. They investigated the potential and feasibility of the desiccant cooling system. There investigations showed that the total annual cooling load of the system was 6428 kWh, reaching a highest value of 809 kWh in the month of December and was lowest in July at 110 kWh. The COP of the system was 0.7 at the collector area of ∼10 m^2. Their assessment also gave methods to improve the coefficient of performance of the system to 1.2 and 60% energy savings, which can be achieved by installing an evacuated tube collector of 20 m^2 and using a larger storage tank. The installed system would also be able to elude carbon dioxide emissions of ∼4.4 tonnes [50].

Guidara and colleagues performed a simulation study of a solar powered desiccant cooling system for office space in Tunisia. Model was simulated for three types of climatic conditions: moderate, hot and dry and cold and humid. Results in all the cases showed that desiccant-based air-conditioning system can provide comfortable environment for the occupants [74].

Table 5. *Results of case studies*

Location	Research type	System	COP	Solar fraction	Case study by
Australia	Analysis	SADCS	0.7	22% (summer)	[50]
Hong Kong	Simulation-optimization	SADCS	1.38 (Mean)	17% (annual)	[51]
Haifa	Experimental investigation	LDS	0.8 (COP_t)	N.A.	[52]
Canada	Performance evaluation	SADCS	0.47 (COP_t)	63% (5 days)	[53]

SADCS, solar-assisted desiccant cooling system; LDS, liquid desiccant system.

Another case study of subtropical region of Hong Kong was done by Fong and colleagues. They performed simulation–optimization of solar-powered desiccant cooling system for an office space where ~50% of the building energy is consumed by air conditioning. An annual average solar fraction of ~17% was obtained with monthly average value ranging between 8% and 33%. An annual average coefficient of performance of the system was 1.38 [51].

Grossman and his colleague constructed a prototype of LDS and monitored its performance for 5 months. They installed the 16 kW_t system in the Mediterranean city of Haifa. Lithium chloride was used as liquid desiccant, and solar collectors were used for the purpose of regeneration. Initial design underwent several changes to improve the design and performance. The thermal coefficient of performance (COP_t) of the system obtained was 0.8 [52].

7.2 Economic evaluation

Salam and Simonson studied the economic, environmental and technical aspects of a membrane LDS. They compared primary energy consumption of four different systems operational in Miami, Florida. Systems include LDS and conventional air-conditioning system. Both of them were investigated with and without energy recovery ventilator. Results showed that the primary energy consumption and total life cycle cost of LDS was lower than conventional system by 19% and 12%, respectively. Addition of energy recovery ventilator improved the difference by 32% for primary energy consumption and 21% for total life cycle cost [75].

A comparison energy and economic evaluation between VCS and hybrid of desiccant system integrated with VCS, by Li and colleagues based on Hong Kong. The performance was further enhanced by using solar thermal energy and ambient air for regeneration. Analysis indicated that replacing the conventional system with hybrid system would reduce the size from 28 kW to 19 kW leading to annual effective energy savings of nearly 6760 kWh. However, the payback period would be 7 years because of the added initial investment of about HK$6360 [76].

8 CONCLUSIONS

Desiccant cooling systems were reviewed in this communication. Liquid desiccant systems were reviewed extensively, while solid and other advanced desiccants were reviewed briefly. Hybrid of LDSs with other system were also reviewed along with the examples some successful case studies. A brief about the literatures on economic evaluation along with the current issues in the LDSs that require attention has also been studied. Conclusions derived from the review are as follows:

(1) Desiccant cooling systems do not use any ozone-depleting refrigerants. Moreover, they can operate successfully on low-grade heat from solar energy, combined heat and power plant or waste heat from factories or chimneys.
(2) Lithium chloride and calcium chloride are the most commonly used desiccants. Lithium chloride is popular because of low vapour pressure and stability while calcium chloride is cheap and easily available. However, both the salts are corrosive nature and require precaution before use. Among all the aqueous salts, potassium formate is least corrosive and can be used as a viable replacement. Two liquid desiccants can also be mixed in suitable proportions to obtain a more cost-effective and efficient liquid desiccant.
(3) Internally cooled dehumidification units help to reduce the heat discharge and allow lower flow rates, which can improve the performance of the system. Two-stage dehumidification unit can help to reduce the irreversibility in the dehumidification process and improves the storage capacity of the desiccant solutions.
(4) Type of packing material selected for dehumidification core is important. Structured packing allow lower pressure drop than random packing but is expensive. On the other hand, random packing material has lower performance because of uneven distribution of liquid desiccant. In dehumidifier core airflow resistance decreases with increase in void ratio. Mass transfer performance increases with the increase in wetted area.
(5) Liquid desiccant can be regenerated using thermal energy either by heating the weak solution or heating the regeneration air using air–water heat exchanger.
(6) Using thermal energy to regenerate the liquid desiccant is not the only option. It can also be done with the help of electro dialysis or reverse osmosis depending on the conditions and suitability.
(7) An adiabatic desiccant system is mostly suitable for drying the air. If cooling is required, then a hybrid system has to be used. A LDS combined with a VCS has a high coefficient of performance.
(8) It can also be combined to an evaporative cooler direct or indirect. A hybrid LDS does not require any refrigerants and thus is more environmentally friendly.
(9) Review of case studies show that desiccant systems have been successful in reducing the latent and sensible load to a considerable extent. Thus, replacing conventional VCS with hybrid desiccant systems would increase the energy savings considerably.
(10) There are concerns that require several design optimizations like carry-over of liquid desiccant at high flow rates, reverse dehumidification at low air humidity ratios and corrosion of the dehumidification unit and storage tank in case of any leakages. Many researches have suggested that the problem of carry-over can be by using micro-porous membrane, which would only allow the air to pass and not the liquid desiccant. However, such membrane also increases the mass transfer resistance.

REFERENCES

[1] Choudhury B, Chatterjee PK, Sarkar JP. Review paper on solar-powered air-conditioning through adsorption route. *Renew Sustai Energy Rev* 2010;**14**: 2189–95.

[2] Remme U, Trudeau N, Graczyk D, *et al. Technology Development Prospects for the Indian Power Sector.* International Energy Agency [IEA], 2011.

[3] Department For Environment Food and Rural Affairs2007 November 6. Available from: http://archive.defra.gov.uk/evidence/statistics/environment/ozone/ozkf12.htm (29 August 2014, date last accessed).

[4] Afonso CFA. Recent advances in building air conditioning systems. *Appl Therm Eng* 2006;**26**:1961–71.

[5] Benhadid-Dib S, Benzaoui A. Refrigerants and their environmental impact Substitution of hydro chlorofluorocarbon HCFC and HFC hydro fluorocarbon. Search for an adequate refrigerant. *Energy Procedia* 2012;**18**:807–16.

[6] Chen Y, Yin YG, Zhang XS. Performance analysis of a hybrid air-conditioning system dehumidified by liquid desiccant with low temperature and low concentration. *Energy Build* 2014;**77**:91–102.

[7] Ahmed CSK, Gandhidasan P, AlFarayedhi AA. Simulation of a hybrid liquid desiccant based air-conditioning system. *Appl Therm Eng* 1997;**17**:125–34.

[8] Sarbu I, Sebarchievici C. Review of solar refrigeration and cooling systems. *Energy Build* 2013;**67**:286–97.

[9] Bradsher K. *Cool Rooms in Asia Warming the Planet*. International Herald Tribune. 2007, February 22. Available from: http://mobile.nytimes.com/2007/02/22/business/worldbusiness/22iht-cool.4691632.html?referrer=&_r=0 (18 August 2014, date last accessed).

[10] Sivak M. Potential energy demand for cooling in the 50 largest metropolitan areas of the world: Implications for developing countries. *Energy Policy* 2009;**37**:1382–4.

[11] Niu XF, Xiao F, Ge GM. Performance analysis of liquid desiccant based air-conditioning system under variable fresh air ratios. *Energy Build* 2010; **42**:2457–64.

[12] Armstrong J. *CIBSE Conscise Handbook*. Norfolk: Page Bros (Norwich) Ltd.Norfolk, 2008.

[13] Mei L, Dai YJ. A technical review on use of liquid-desiccant dehumidification for air-conditioning application. *Renew Sustain Energy Rev* 2008;**12**:662–89.

[14] Baniyounes AM, Ghadi YY, Rasul MG, *et al*. An overview of solar assisted air conditioning in Queensland's subtropical regions, Australia. *Renew Sustain Energy Rev* 2013;**26**:781–804.

[15] Wang XL, Cai WJ, Lu JG, *et al*. A hybrid dehumidifier model for real-time performance monitoring, control and optimization in liquid desiccant dehumidification system. *Appl Energy* 2013;**111**:449–55.

[16] Liu XH, Yi XQ, Jiang Y. Mass transfer performance comparison of two commonly used liquid desiccants: LiBr and LiCl aqueous solutions. *Energy Conversion Manag* 2011;**52**:180–90.

[17] Qiu GQ, Riffat SB. Experimental investigation on a novel air dehumidifier using liquid desiccant. *Int J Green Energy* 2010;**7**:174–80.

[18] Qiu GQ, Riffat SB, Zhu J. Novel liquid regeneration system with solar evacuated tubes and evaporative bed. *J Energy Institute* 2008;**81**:92–6.

[19] Patil KR, Tripathi AD, Pathak G, *et al*. Thermodynamic properties of aqueous-electrolyte solutions.1. vapor-pressure of aqueous-solutions of LICL, LIBR, and LII. *J Chem Eng Data* 1990;**35**:166–8.

[20] Beyer R, Steiger M. Vapor Pressure Measurements of NaHCOO + H(2)O and KHCOO + H(2)O from 278 to 308K and Representation with an Ion Interaction (Pitzer) Model. *J Chem Eng Data* 2010;**55**:830–8.

[21] Li XW, Zhang XS, Cao RQ, *et al*. Progress in selecting desiccant and dehumidifier for liquid desiccant cooling system. *Energy Build* 2012;**49**:410–8.

[22] Ahmed SY, Gandhidasan P, Al-Farayedhi AA. Thermodynamic analysis of liquid desiccants. *Solar Energy* 1998;**62**:11–8.

[23] Mandegari MA, Pahlavanzadeh H. Introduction of a new definition for effectiveness of desiccant wheels. *Energy* 2009;**34**:797–803.

[24] Luo YM, Yang HX, Lu L, *et al*. A review of the mathematical models for predicting the heat and mass transfer process in the liquid desiccant dehumidifier. *Renew Sustain Energy Rev* 2014;**31**:587–99.

[25] Xiong ZQ, Dai YJ, Wang RZ. Development of a novel two-stage liquid desiccant dehumidification system assisted by CaCl2 solution using exergy analysis method. *Appl Energy* 2010;**87**:1495–504.

[26] Xiong ZQ, Dai YJ, Wang RZ. Investigation on a two-stage solar liquid-desiccant (LiBr) dehumidification system assisted by CaCl2 solution. *Appl Therm Eng* 2009;**29**:1209–15.

[27] Kumar R, Asati AK. Simplified mathematical modelling of dehumidifier and regenerator of liquid desiccant system. *Int J Curr Eng Technol* 2014;**4**:557–63.

[28] Das RS, Jain S. Experimental performance of indirect air-liquid membrane contactors for liquid desiccant cooling systems. *Energy* 2013;**57**:319–25.

[29] Bassuoni MM. An experimental study of structured packing dehumidifier/regenerator operating with liquid desiccant. *Energy* 2011;**36**:2628–38.

[30] Qi RH, Lu L, Yang HX, *et al*. Investigation on wetted area and film thickness for falling film liquid desiccant regeneration system. *Appl Energy* 2013;**112**:93–101.

[31] Liu XH, Jiang Y, Xia JJ, *et al*. Analytical solutions of coupled heat and mass transfer processes in liquid desiccant air dehumidifier/regenerator. *Energy Conver Manag* 2007;**48**:2221–32.

[32] Liu XH, Chang XM, Xia JJ, *et al*. Performance analysis on the internally cooled dehumidifier using liquid desiccant. *Build Environ* 2009;**44**:299–308.

[33] Mohammad AT, Bin Mat S, Sulaiman MY, *et al*. Theoretical study of the effect of liquid desiccant mass flow rate on the performance of a cross flow parallel-plate liquid desiccant-air dehumidifier. *Heat Mass Transfer* 2013; **49**:1587–93.

[34] Alosaimy AS, Hamed AM. Theoretical and experimental investigation on the application of solar water heater coupled with air humidifier for regeneration of liquid desiccant. *Energy* 2011;**36**:3992–4001.

[35] Yin YG, Zhang XS, Peng DG, *et al*. Model validation and case study on internally cooled/heated dehumidifier/regenerator of liquid desiccant systems. *Int J Thermal Sci* 2009;**48**:1664–71.

[36] Cheng Q, Xu Y, Zhang XS. Experimental investigation of an electrodialysis regenerator for liquid desiccant. *Energy Build* 2013;**67**:419–25.

[37] Al-Sulaiman FA, Gandhidasan P, Zubair SM. Liquid desiccant based two-stage evaporative cooling system using reverse osmosis (RO) process for regeneration. *Appl Therm Eng* 2007;**27**:2449–54.

[38] Yin YG, Qian JF, Zhang XS. Recent advancements in liquid desiccant dehumidification technology. *Renew Sustain Energy Rev* 2014;**31**:38–52.

[39] Katejanekarn T, Chirarattananon S, Kumar S. An experimental study of a solar-regenerated liquid desiccant ventilation pre-conditioning system. *Solar Energy* 2009;**83**:920–33.

[40] Jradi M, Riffat S. Tri-generation systems: energy policies, prime movers, cooling technologies, configurations and operation strategies. *Renew Sustain Energy Rev* 2014;**32**:396–415.

[41] Kessling W, Laevemann E, Peltzer M. Energy storage in open cycle liquid desiccant cooling systems. *Int J Refrig Revue Internationale Du Froid* 1998; **21**:150–6.

[42] Kessling W, Laevemann E, Kapfhammer C. Energy storage for desiccant cooling systems component development. *Solar Energy* 1998;**64**:209–21.

[43] Yin YG, Zhang XS, Chen ZQ. Experimental study on dehumidifier and regenerator of liquid desiccant cooling air conditioning system. *Build Environ* 2007;**42**:2505–11.

[44] Kim MH, Park JS, Jeong JW. Energy saving potential of liquid desiccant in evaporative-cooling-assisted 100% outdoor air system. *Energy* 2013;**59**:726–36.

[45] Henning HM, Erpenbeck T, Hindenburg C, *et al*. The potential of solar energy use in desiccant cooling cycles. *Int J Refrig Revue Internationale Du Froid* 2001;**24**:220–9.

[46] Khalil A. An experimental study on multi-purpose desiccant integrated vapor-compression air-conditioning system. *Int J Energy Res* 2012;**36**: 535–44.

[47] She XH, Yin YG, Zhang XS. Thermodynamic analysis of a novel energy-efficient refrigeration system subcooled by liquid desiccant dehumidification and evaporation. *Energy Conver Manag* 2014;**78**:286–96.

[48] Pang SC, Masjuki HH, Kalam MA, *et al*. Liquid absorption and solid adsorption system for household, industrial and automobile applications: a review. *Renew Sustain Energy Rev* 2013;**28**:836–47.

[49] Cengel YA, Ghajar AJ. *Heat and Mass Transfer: Fundamentals and Applications + EES DVD for Heat and Mass Transfer*. 4 ed. United States: McGraw Hill Higher EducationUnited States; 2010.

[50] Baniyounes AM, Liu G, Rasul MG, *et al*. Analysis of solar desiccant cooling system for an institutional building in subtropical Queensland, Australia. *Renew Sustain Energy Rev* 2012;**16**:6423–31.

[51] Fong KF, Chow TT, Lin Z, *et al*. Simulation-optimization of solar-assisted desiccant cooling system for subtropical Hong Kong. *Appl Therm Eng* 2010;**30**:220–8.

[52] Gommed K, Grossman G. Experimental investigation of a liquid desiccant system for solar cooling and dehumidification. *Solar Energy* 2007;**81**:131–8.

[53] Crofoot L, Harrison S. Performance evaluation of a liquid desiccant solar air conditioning system. *1st International Conference on Solar Heating and Cooling for Buildings and Industry (Shc 2012)* 2012;**30**:542–50.

[54] Bassuoni MM. A simple analytical method to estimate all exit parameters of a cross-flow air dehumidifier using liquid desiccant. *J Adv Res* 2014;**5**:175–82.

[55] Koronaki IP, Christodoulaki RI, Papaefthimiou VD, *et al*. Thermodynamic analysis of a counter flow adiabatic dehumidifier with different liquid desiccant materials. *Appl Therm Eng* 2013;**50**:361–73.

[56] Liu XH, Qu KY, Jiang Y. Empirical correlations to predict the performance of the dehumidifier using liquid desiccant in heat and mass transfer. *Renew Energy* 2006;**31**:1627–39.

[57] Gandhidasan P. Quick performance prediction of liquid desiccant regeneration in a packed bed. *Solar Energy* 2005;**79**:47–55.

[58] Gandhidasan P. A simplified model for air dehumidification with liquid desiccant. *Solar Energy* 2004;**76**:409–16.

[59] Gandhidasan P, Mohandes MA. Artificial neural network analysis of liquid desiccant dehumidification system. *Energy* 2011;**36**:1180–6.

[60] Parmar H, Hindoliya DA. Artificial neural network based modelling of desiccant wheel. *Energy Build* 2011;**43**:3505–13.

[61] Li XW, Zhang XS, Wang F. A kinetic mass transfer model of liquid dehumidification for liquid desiccant cooling system. *Energy Build* 2013;**61**:93–9.

[62] Jain S, Tripathi S, Das RS. Experimental performance of a liquid desiccant dehumidification system under tropical climates. *Energy Conver Manag* 2011;**52**:2461–6.

[63] Isetti C, Nannei E, Magrini A. On the application of a membrane air-liquid contactor for air dehumidification. *Energy Build* 1997;**25**:185–93.

[64] Kumar R, Dhar PL, Jain S, *et al*. Multi absorber stand alone liquid desiccant air-conditioning systems for higher performance. *Solar Energy* 2009;**83**: 761–72.

[65] Ge GM, Moghaddam DG, Abdel-Salam AH, *et al*. Comparison of experimental data and a model for heat and mass transfer performance of a liquid-to-air membrane energy exchanger (LAMEE) when used for air dehumidification and salt solution regeneration. *Int J Heat Mass Transfer* 2014;**68**:119–31.

[66] Liang CH. Research on a refrigeration dehumidification system with membrane-based total heat recovery. *Heat Transfer Eng* 2014;**35**:1043–9.

[67] Zhao Y, Ge TS, Dai YJ, *et al*. Experimental investigation on a desiccant dehumidification unit using fin-tube heat exchanger with silica gel coating. *Appl Therm Eng* 2014;**63**:52–8.

[68] Ng EP, Mintova S. Nanoporous materials with enhanced hydrophilicity and high water sorption capacity. *Microporous Mesoporous Mater* 2008;**114**: 1–26.

[69] Goldsworthy M, White SD. Limiting performance mechanisms in desiccant wheel dehumidification. *Appl Therm Eng* 2012;**44**:21–8.

[70] Lee J, Lee DY. Sorption characteristics of a novel polymeric desiccant. *Int J Refrig Revue Internationale Du Froid* 2012;**35**:1940–9.

[71] Jia CX, Dai YJ, Wu JY, *et al*. Use of compound desiccant to develop high performance desiccant cooling system. *Int J Refrig Revue Internationale Du Froid* 2007;**30**:345–53.

[72] Guo P, Wong-Foy AG, Matzger AJ. Microporous coordination polymers as efficient sorbents for air dehumidification. *Langmuir* 2014;**30**:1921–5.

[73] Stevens DI, Braun JE, Klein SA. An effectiveness model of liquid desiccant system heat mass exchangers. *Solar Energy* 1989;**42**:449–55.

[74] Guidara Z, Elleuch M, Ben Bacha H. New solid desiccant solar air conditioning unit in Tunisia: design and simulation study. *Appl Therm Eng* 2013;**58**:656–63.

[75] Abdel-Salam AH, Simonson CJ. Annual evaluation of energy, environmental and economic performances of a membrane liquid desiccant air conditioning system with/without ERV. *Appl Energy* 2014;**116**:134–48.

[76] Li YT, Lu L, Yang HX. Energy and economic performance analysis of an open cycle solar desiccant dehumidification air-conditioning system for application in Hong Kong. *Solar Energy* 2010;**84**:2085–95.