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Solar Powered Dehumidification Systems Using Desert Evaporative Coolers: Review

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***Abstract*— This paper gives a detailed account of the general features of the major desiccant regeneration techniques and configurations of the related systems; meanwhile, attention has been paid to both technological development of solar powered regenerator, which is a key component of the liquid-desiccant dehumidification system. Studies to improve the system performance have been discussed. Benefits and conditions of the use of liquid desiccant for dehumidification purposes have been stated. It is clear from the survey that the desiccant dehumidification is more energy-efficient compared with the conventional vapor compression system. Moreover, new configurations of the solar regenerator, to improve the system performance, have been demonstrated. Some new hybrid systems that greatly expand the desiccant in residential applications, as well as effectively promoting the single system's performance, are also introduced.**

***Index Terms* — Dehumidification, Cooling, Liquid desiccant, Solar, Regenerator**

I. INTRODUCTION

Conventional cooling technologies that utilize harmful refrigerants consume more energy and cause peak loads leading to negative environmental impacts. As the world grapples with the energy and environmental crisis, there is an urgent need to develop and promote environmentally benign sustainable cooling technologies. Solar/desiccant cooling is one such promising technology, given the fact that solar energy is the cheapest and widely available renewable energy that matches the cooling load requirements. More research and development on enhanced solar cooling techniques coupled with a simpler, energy efficient and cost effective thermal storage system, possessing higher energy density would lead to economic competitiveness.

There are many demonstration experiences in solar/desiccant cooling systems. However, the success of solar/desiccant cooling technologies will depend on the encouragement and promotional schemes offered by the policymakers, and the efforts undertaken by the manufacturers to improve the cost efficiency as well in developing better technologies. In the desiccant cooling system, energy is mainly consumed to regenerate the desiccant material by heating to a specified temperature.

Numerous researchers [1-7] have studied the low cost and low regeneration temperature of desiccant material, and the optimization of desiccant application to produce more competitive energy. The use of heat to regenerate desiccant material in a drying system has limitations in energy saving. However, the use of low energy or free available energy such as solar energy and waste heat from industrial processes for regeneration of desiccant material will make the system more cost-effective. The use of solar energy for the regeneration process of desiccant material has been studied extensively because it is a free energy source. The initial cost of solar energy is quite expensive, but in the long run, it can contribute to savings in overall cost. Therefore, the payback period should be considered. However, solar radiation is weather-dependent; therefore, back- up energy or energy storage is required to continue the drying process when solar energy is not available. The use of evaporative coolers as the mass exchange equipment can be applied in liquid desiccant systems. This application can reduce the installation cost of such systems because the evaporative coolers are available in the market with lower cost when compared with designing and manufacturing specified mass exchange equipments for such systems.

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II. CONCEPT OF THE THERMALLY ACTIVATED DESICCANT COOLING TECHNOLOGIES

Fig. 1 shows the operational concept and diagram of the desiccant-based ventilation and air-conditioning system [8]. The processed air from the desiccant dehumidifier becomes hot due to the release of the heat of condensation and heat of sorption. Heat recovery devices are used to recover this energy. The condition of the air after the heat recovery becomes warm and dry.

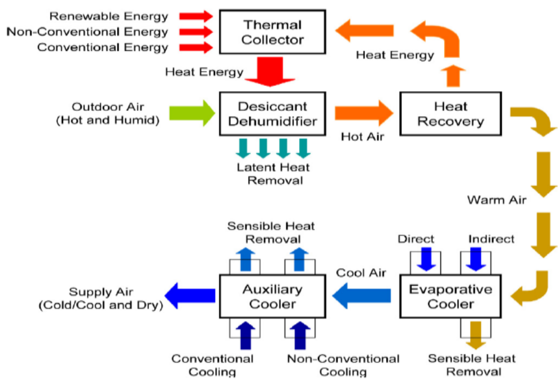

Fig.1 General concept of the thermally activated desiccant cooling technologies [8].

As in many applications, the air condition is still above the thermal comfort temperature, so that evaporative cooling process is applied by either direct addition of air moisture or indirect addition of air moisture in secondary air stream. The application of evaporative cooling process reduces the air temperature with either slight increase of air moisture content or constant air moisture content.

2.1. Benefits of the desiccant cooling

Desiccant materials are used for air-conditioning applications with advantages in the following conditions [9].

a) The latent load is large in comparison to the sensible load.
b) The cost of energy to regenerate the desiccant is low when compared with the cost of energy to dehumidify the air by chilling it below its dew point.
c) The moisture control level required in the space would require chilling the air to subfreezing dew points if compression refrigeration alone were used to dehumidify the air.
d) The temperature control level required by the space or process requires continuous delivery of air at subfreezing temperatures.

2.2. Ideal dehumidification process

Ideal dehumidification process is achieved by both condensing dehumidification and liquid desiccant dehumidification methods, and the minimum input work and ideal COP of the two dehumidification methods are presented by Zhang L et al. [10]. For liquid desiccant dehumidification, the humidity ratio of regeneration air is the most important influencing factor of COP. For condensing dehumidification, the temperature of heat sink is the most important influencing factor of COP. The essence of dehumidification is transportation of moisture between indoor and outdoor two different humidity ratios. Exhaust heat into heat sink in condensing dehumidification method and exhaust moisture into moisture sink in liquid desiccant dehumidification mode can be compared, due to the fact that heat and moisture are unified in saturated line. The two dehumidification modes will have the same performance, when heat sink of condensing dehumidification is dew point of outdoor air by indirect evaporation or outdoor air is saturated. The ideal dehumidification process means removing moisture per unit mass from indoor air state to outdoor air state with minimum input work. The assumptions of ideal dehumidification process are discussed in details in [10]. Schematic diagram of ideal dehumidification process is shown in Fig. 2.

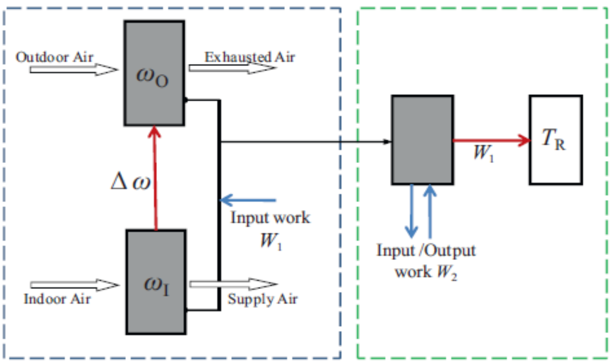

Fig. 2. Schematic diagram of ideal dehumidification process [10].

2.3. Comparison between desiccant system and vapor compression air- conditioning systems

The comparison between desiccant dehumidification system and conventional vapor compression air-conditioning systems is listed in Table 1, and CACS stands for central air-conditioning system, while LDDS stands for liquid-desiccant dehumidification system.

Table 1- Comparison between desiccant dehumidification system and vapor compression system

Parameter	Vapor compression	Desiccant
Operation cost	High	low
Energy source	Mainly electricity	Low-grade energy
Control over humidity	Average	Accurate
Indoor air quality	Average	Good
System installment	Average	Complicate
Energy storage capacity	Mainly not applicable	Good
Installation cost	Low	High
System control	Average	Complicate

Liquid-desiccant dehumidification has been proved to be an effective method to extract the moisture of air with relatively less energy consumption, especially compared with conventional vapor compression system. The conventional dehumidification mode with desiccant solution has been improved or replaced by newly emerged energy-saving systems with better performance. L. Mei and Y.J. Dai [11] presented a detailed account of the general features of the major desiccant dehumidification techniques and configurations of the related systems. They paid attention to both technological and theoretical development of regenerator, which is an indispensable component of the liquid-desiccant dehumidification system. Moreover, they provided a summary of the experimental and analytical studies to optimize the system performance. They also introduced some new hybrid systems that greatly expand the desiccant dehumidification technique in industrial and residential applications, as well as effectively promoting the single system.

2.4. Psychrometric processes for conventional and desiccant cooling systems

The latent load might be handled by reducing cooling temperature below the dew-point temperature to increase the condensation until the desired humidity level is reached [12]. Then, the air is reheated to bring the temperature back to the supply point. This overcool/ reheat scheme is energy-inefficient since it needs additional energy to overcool and reheat the air. Fig. 3 depicts the operational processes of the conventional air conditioning system which uses the overcool (OC) /reheats (CS) operation to achieve a particular supply condition. On the same graph, the desiccant dehumidification (OD) with subsequent sensible cooling (DS) is also presented.

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It is clear from the graph that the desiccant dehumidification with subsequent cooling is more energy-efficient compared with the conventional vapor compression system. However, the use of low energy or free available energy such as solar energy and waste heat from industrial processes for regeneration of desiccant material will make the system more cost-effective.

2.5. Advantages of the liquid desiccant over solid desiccants

Liquid desiccants have many advantages over solid desiccants. Their capacity to absorb moisture is generally greater than that of solid desiccants [13-15]. Liquid desiccants require lower regenerating temperature, mostly in the range of 40–70 ºC while it is in the range of 60–115 ºC for a solid desiccant. This allows the use of low grade heat sources such as solar energy or waste heat. Besides, liquid desiccants can be stored in form of concentrated solution for use during periods when solar energy is absent, and thus offer more flexible operational characteristics. The liquid desiccants are attractive because of their operational flexibility and their capability of absorbing pollutants and bacteria. Their disadvantage is their carryover in the process air stream during the dehumidification operation. Technologically, the equipment providing air/solution contact surface (contactor) can be a wetted wall/falling film absorber, a spray chamber or a packed tower. The packed towers are subdivided into regular (structured) or irregular (random) packing modes.

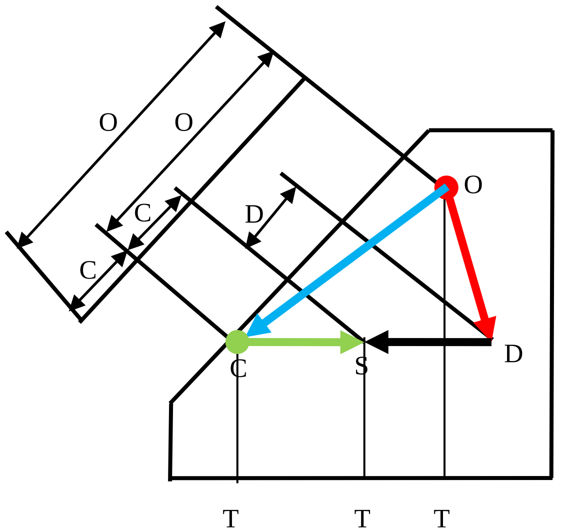

Fig.3. Psychrometric processes for conventional and desiccant cooling systems

O: outside conditions; D: dehumidification; S: supply point; C: cooling with dehumidification
OC: over cooling; CS: re heating; DS: sensible cooling; OS: total load (cooling and heating)

The liquid desiccant assisted air conditioning can achieve up to 40% of energy savings with regard to traditional air conditioning system and those savings become even greater when the calorific energy needed for regeneration is drawn from waste heat, solar energy or any other free energy sources [16-26].

III. LIQUID DESICCANT COOLING

In a liquid desiccant cooling system, the liquid desiccant circulates between an absorber and a regenerator in the same way as in an absorption system. Main difference is that the equilibrium temperature of a liquid desiccant is determined not by the total pressure but by the partial pressure of water in the humid air to which the solution is exposed to. A typical liquid desiccant system is shown in Fig. 4. In the dehumidifier of Fig. 4, a concentrated solution is sprayed at point A over the cooling coil at point B while ambient or return air at point 1 is blown across the stream.
The solution absorbs moisture from the air and is simultaneously cooled down by the cooling coil. The results of this process are the cool dry air at point 2 and the diluted solution at point C.

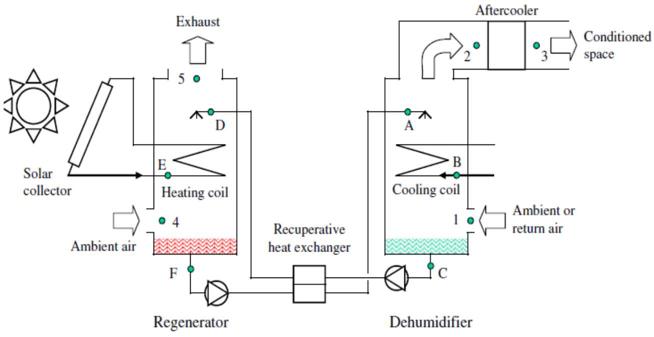

Fig. 4. A liquid desiccant cooling system with solar collector [3].

Eventually an after cooler cools this air stream further down. In the regenerator, the diluted solution from the dehumidifier is sprayed over the heating coil at point E that is connected to solar collectors and the ambient air at point 4 is blown across the solution stream. Some water is taken away from the diluted solution by the air while the solution is being heated by the heating coil. The resulting concentrated solution is collected at point F and hot humid air is rejected to the ambient at point 5. A recuperative heat exchanger preheats the cool diluted solution from the dehumidifier using the waste heat of the hot concentrated solution from the regenerator, resulting in a higher COP.

3.1. Liquid desiccant solutions

Several liquid desiccants, including aqueous solutions of organic compound (e.g., tri ethylene glycol) and aqueous solutions of inorganic salts (e.g., lithium chloride), have been employed to remove water vapor from air. Gommed and Grossman [27] investigated the use of liquid desiccant system, which absorbs humidity from the process air by direct contact with desiccant and desiccant regeneration by direct contact with external air stream in a 16 kW solar cooling and dehumidification system using LiCl/water as the working fluid and reported a COP of 0.8. The choice of desiccant will have a significant effect on the design of the desiccant cooling system. Glycols and solutions of halide salts are routinely used in industrial equipment, each having important advantages and disadvantages. Halide salts such as lithium chloride and lithium bromide are very strong desiccants: a saturated solution of lithium bromide can dry air to 6% relative humidity and lithium chloride to 11%.

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Halide salts are corrosive to most ferrous and nonferrous metals. Aqueous solutions of lithium bromide are commonly used in absorption chillers. But these systems are closed, so oxygen levels can be kept low and corrosion inhibitors can be used. Glycols are the second class of liquid desiccants now used in industrial equipment. Both triethylene and propylene glycol have low toxicity, and their compatibility with most metals has led several researchers to use them in desiccant cooling systems. All glycols have one undesirable characteristic: they are volatile. Salts of weak organic acids, such as potassium or sodium formate and acetate, are less corrosive alternatives to halide salts that are also not volatile. Formate salts have the advantage of being significantly less viscous than acetate salts at concentrations with equivalent equilibrium relative humidities [28].

Calcium chloride is both hygroscopic and deliquescent. Thus, under common ambient conditions, solid material will absorb moisture from the air until it dissolves. Calcium chloride solutions will absorb moisture until equilibrium is reached between the water vapor pressure of the solution and that of the air. If the humidity of the air increases, more moisture is absorbed by the solution. If it decreases, water evaporates from the solution into the air. Figure 5 shows the equilibrium water vapor pressure of various forms of calcium chloride at various temperatures. The saturated solution curve shows the temperature and humidity conditions under which calcium chloride transitions between solid and liquid phases. At 30°C (85°F), a typical summer temperature, the water vapor pressure needed to liquefy calcium chloride is 7 mmHg, corresponding to 22 percent relative humidity. Since the values of summer humidity are usually higher than 22 percent, calcium chloride liquid, flakes or pellets will pick up water from the air and either dilute or dissolve. This property makes calcium chloride useful in dehumidification and dust control applications.

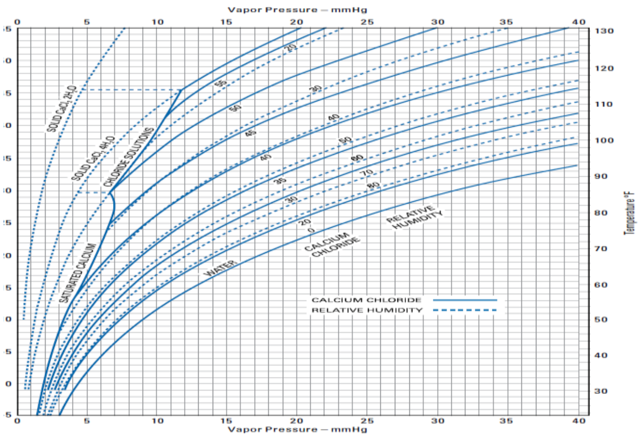

Fig.5. Equilibrium water vapor pressure of various forms of calcium chloride at various temperatures [29]

The rate at which moisture is absorbed by a given quantity of calcium chloride depends on application specific variables that control the degree of contact between the air and the calcium chloride, such as surface area and air movement.

While it is difficult to estimate the rate at which moisture is absorbed, it is not difficult to determine the maximum amount of water that can be absorbed per pound of calcium chloride at any given humidity and temperature [29]. Attempts for mixing desiccant solutions to improve the thermo-physical properties have been carried by different investigators. Ertas et al. [30] have analyzed the thermal properties of combinations of lithium chloride and calcium chloride. There were five different combinations according to the changed LiCl/CaCl2 ratio. The results showed that the 100% LiCl group was the lowest vapor pressure under different temperatures. Ahmed et al. [31] studied the rules of predicting thermo-physical properties of 50% concentration of LiCl and 50% $CaCl_2$. The properties include vapor pressure, viscosity, and density. The results show that the interaction parameter works very well for calculating the viscosity of the mixture but doesn't function well for calculating vapor pressure and density. Hassan and Salah [32] studied a mixture of 50% of the weight of water calcium chloride and 20% calcium nitrate. They studied the physical properties of the mixture, such as viscosity, vapor pressure, density as well as the heat and mass transfer process. As compared with vapor pressure of 50% CaCl2 solution, the results of the study show a significant increase in vapor pressure. Li et al. [33] proposed a novel method that mixes LiCl and CaCl2. In their work, they divided the liquid desiccant into five groups: Group 1 (pure LiCl with mass fraction 39%), Group 2 (mixed LiCl–CaCl2 solution with mass fraction of 5% for CaCl2), Group 3(35% LiCl and 10% CaCl2), Group 4 (33% LiCl and 15% CaCl2), and Group 5(31.2% LiCl and 20% CaCl2). The experimental results show that the fifth groups have the best dehumidification effect.

3.2. Selection of the liquid desiccant

The selection of the liquid desiccant is decisive in the overall performance of the dehumidification system, and will exert an immediate influence on the mass of dehumidification. Its selection depends on various operating parameters, such as boiling point elevation, energy storage density, regeneration temperature, thermo-physical properties, availability, cost, etc. Among the above parameters, the surface vapor pressure is one of major concern and has been investigated extensively and thoroughly. Lithium bromide, lithium chloride, triethylene glycol are among the most widely used single desiccants, their surface vapor pressure at low temperature and high concentration are lower than that of the humid process air.

Investigations and experiments found that calcium chloride is the cheapest and most readily available desiccant, but its vapor pressure at a given temperature is relatively high, and its unstable conditions depending on inlet air conditions and desiccant concentration in solution limit its widespread use. Lithium chloride is the most stable desiccant with advantageously low vapor pressure, but its cost is slightly higher compared with others. The cost and vapor pressure of lithium bromide are intermediate. Triethylene glycol is the earliest used desiccant in liquid desiccant dehumidification systems, but the liquid residence caused by its high viscosity make the system operation unstable. Besides, triethylene glycol has a very low surface vapor pressure, which causes some of them to evaporate into the air flowing into the conditioned areas. Owing to the difference of the purity of the metal-salt, the surface vapor pressure of the liquid desiccants often varies. Experimental measurement is an important method but not a universal method due to the capital support.

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Lithium chloride and calcium chloride are the universal desiccants mostly used to get cost-effective mixture in different weight combinations in the open literature [30-33].

IV. OPEN SOLAR COLLECTOR/ REGENERATOR

Regeneration of the desiccant material at low temperature will give more benefits in terms of energy efficiency. The use of renewable energy or waste heat from any system will also reduce the operation cost of the desiccant system. Common regeneration methods use solar energy, electrical heater, and waste heat. Some studies conducted used other regeneration methods to identify the most effective and economical method. Many attempts have been made to use solar energy for regenerating weak absorbent solutions. Different regenerator designs have been studied by researchers [34-36].

The regenerator is one of the key components in liquid desiccant air-conditioning systems, in which desiccant is concentrated and can be reused in the system. The heat required for regenerating the weak desiccant solution is supplied into the regenerator by either hot air or hot desiccant solution. Solar collector/regenerator (C/R) systems can achieve liquid regeneration at lower temperatures which is suitable for buildings with high outdoor air requirements in high humidity areas [37-41]. Several solar-driven refrigeration systems have been proposed and most of them are economically justified. These systems include sorption systems containing liquid/vapor or solid/vapor absorption/adsorption, vapor compression systems, and hybrid desiccant vapor compression systems [42]. Different regenerator designs have been examined and a variety of theoretical models have been employed to analyze the regeneration process [43-48]. The concept of open absorption cooling has been demonstrated by Kakabayev and Khandurdyev [37]. They presented an analytical procedure for calculating the mass of water evaporated from the weak solution in the regenerator in terms of climatic conditions and solution properties at the regenerator inlet. Fig. 6 demonstrates the principles of operation of the open absorption cooling system.

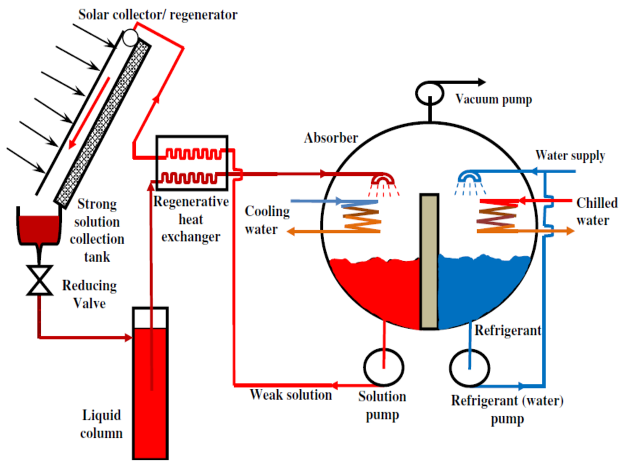

Fig. 6. Open Absorption Regeneration System

In the case of solar energy, solar air or water heaters could be used for the regeneration. However, by using direct solar regenerators where the absorbent solution is itself the heat collecting fluid, the regeneration process could be made more effective. The absorber temperature is or less equal to the collector-plate temperature. The regeneration chamber is also eliminated. Forced parallel flow type solar collector/ regenerator is designed and tested by Alizadeh and Saman [49]. The regenerator has been designed and optimized and the prototype of the solar collector / regenerator has been built and tested. Calcium chloride has been used as the absorbent solution. The regenerator has been designed and optimized and the prototype of the solar collector / regenerator has been built and tested (see figure 7). The results of the tests conducted as a parametric analysis indicate that the air and solution mass flow-rates and the climatic conditions affect the regenerator performance. It was concluded that the proposed solar collector / regenerator performs satisfactorily under the summer conditions of Adelaide, Australia.

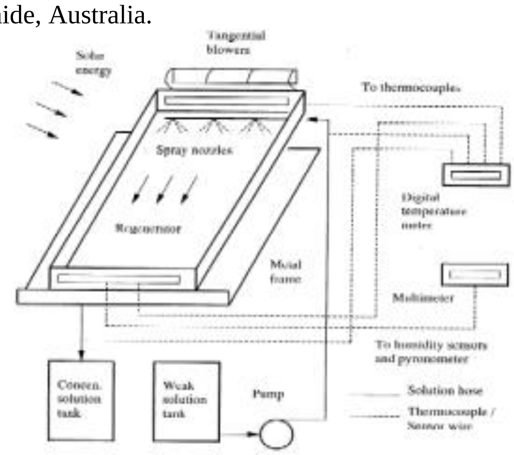

Fig.7. Parallel flow desiccant regenerator [49]

The regeneration of liquid solution using cross flow of air stream with flowing film of desiccant on the surface of a solar collector/regenerator has been investigated by Kabeel [50]. To evaluate the effect of cross flow of air stream on the performance of the unit, two identical units are constructed and tested in the same conditions of operation. One of the two units was augmented with air blower. The absorber plate is a black cloth layer. The forced air stream, which flows across the absorber removes the moisture from the liquid solution. The regeneration in the other collector/regenerator unit is under free convection. The results show enhancement of regeneration efficiency for the forced cross flow compared with the free convection.

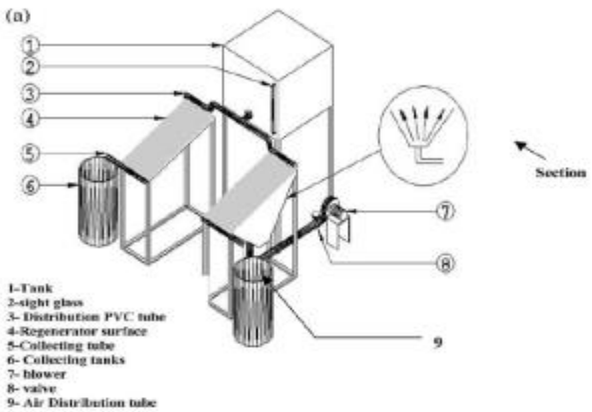

Fig. 8. Cross flow desiccant regenerator [50]

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Solar air pretreatment liquid collector/regenerator is presented in [51]. The heat and mass transfer process was simulated in the novel liquid regenerator and the conclusions show that the increment of solution outlet concentration increases 70%, regeneration efficiency augments 45.7% and storage capacity increases 44% as effective solution proportion falls from 100% to 62%. The system of solar air pretreatment collector/regenerator shown in Fig. 9 is composed of air cycle and solution cycle. The air cycle consists of blower, air pretreatment unit and solar collector/regenerator. The air cycle is an open cycle. The solution cycle is consisted of antisepsis solution pump, air pretreatment unit, collector/regenerator and liquid heat exchanger. The diluted solution out of the air pretreatment unit and the dehumidifier enters liquid heat exchanger where it is firstly heated by the strong solution leaving from the collector/regenerator and then is delivered by antisepsis solution pump into the solar collector/regenerator where the water in the solution is removed by air stream and the solution is regenerated, later comes back to the liquid heat exchanger preheating the cold diluted solution, finally flows into the dehumidifier and air pretreatment unit, respectively, where the solution is diluted by absorbing water vapor in air stream. In this way, a close circulation of dilution, regeneration and once more dilution is constructed. According to whether the flow directions of solution and air stream in the C/R are the same, or not, the solution C/R is divided into two working modes of parallel current and counter-current.

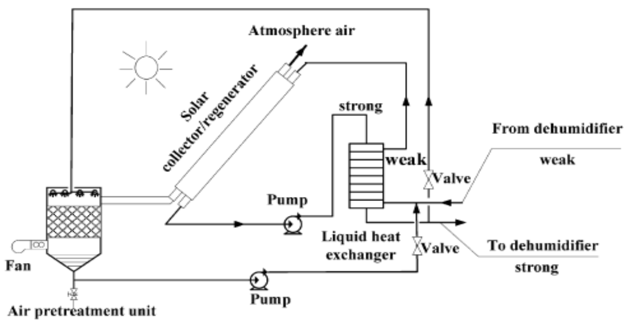

Fig. 9. Schematic diagram of solar air pretreatment collector/regenerator [51].

The effects of changing five key variables on the performances of this liquid desiccant air-conditioning system have been studied. Increasing the inlet solution temperature in regenerator can improve the system's performance, but it is also restricted by the crystallization limit of desiccant solution. The appropriate mass fluxes of air in the dehumidifier and the regenerator should be accommodated to get this liquid desiccant system performance better [52].

Theoretical and experimental investigation on the application of flat plate solar water heater coupled with air humidifier for regeneration of liquid desiccant has been presented in [53]. The heated water from the storage tank of the solar heating system is circulated in a finned tube air heater. Hot air from the air heater is blown through a packing of a honeycomb type for the purpose of regeneration of calcium chloride ($CaCl_2$) solution. The system comprises a solar water heater with storage tank connected to the air/water heat exchanger. Hot air from the heat exchange is blown to the air humidifier, which functions in this study as a regenerator. Calcium chloride solution is applied as the working desiccant in this study.

L. Yutong and Y. Hongxing [54] presented the numerical simulation results of an open cycle liquid desiccant dehumidification system, attempts to obtain the best configurations of the solar assisted air-conditioning system and to validate the feasibility of using a liquid desiccant dehumidification system to handle the latent load and improve the energy efficiency of HVAC systems. Firstly, based on the steady state simulation model of a solar collector/regenerator (C/R) system, the energy performance for using exhaust air to regenerate the weak desiccant solution and heating the solution to a temperature higher than the equilibrium value were tested and discussed for different lengths of the collector/regenerator panels. It was found that the thermodynamic performance was significantly improved and it was possible to shorten the length of the solar C/R without degrading the performance greatly. Secondly, the transient performance of the open cycle liquid desiccant dehumidification system was simulated for the weather conditions of Hong Kong. The energy saving, compared with a conventional vapor compression system, is in the range of 25–50%. The higher the portion of latent load in the total ventilation load, the more the energy saving.

A corrugated blackened surface was used by Elsarrag [55] to heat the desiccant and an air flow was used to regenerate the solution. The effect of the liquid to air flow rate ratio, the desiccant temperature, the desiccant concentration and the inlet air humidity ratio on the evaporation rate was carried out. A wide range of liquid to air flow rate ratios were used. The optimum value of the liquid to air flow rate ratio was reported. The schematic diagram of the proposed unit is shown in Fig. 10. The unit has a corrugated blackened tilted surface and an effective solar area of 1 m^2. The galvanized corrugated steel sheet is coated by a thin layer of anticorrosion material and is covered by a single glazing with an air gap of about 420 mm above the corrugated surface. Galvanized steel corrugated sheeting was selected for its strength and resistance to corrosion. The weak calcium chloride is heated by solar energy during the day. The desiccant circulating pump is controlled by a digital controller using the sensor fixed on the blackened surface. The controller is set to the required regeneration temperature. When the blackened surface temperature reaches the set point, the pump circulates the weak desiccant from the storage tank to the tilted solar surface. The weak desiccant flows as a thin film over the blackened corrugated surface where its temperature rises while it comes down to the bottom. As the blackened surface is cooled down, the controller switches off the pump and a slight increase in the desiccant temperature occurs. This procedure continues automatically until the desiccant reaches the desired regeneration temperature (the set temperature).

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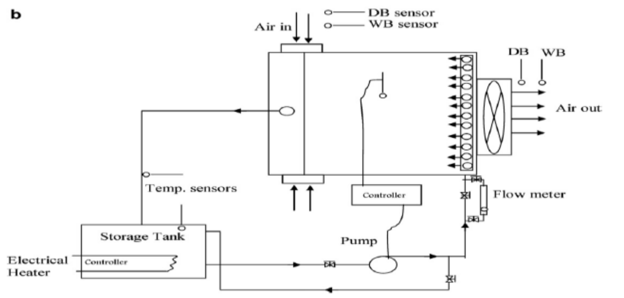

Fig. 10. Schematic diagram of the unit presented by Elsarrag [55].

Hamed et al. [56] proposed a rotating wick made of double layer cotton cloth as a desiccant solar regenerator. The blackened wick surface, which is impregnated with desiccant solution, moves between two rotating pulleys at an inclination angle of 20 degree. Solar radiation incident on the wick surface regenerates the liquid desiccant in the wick. Calcium Chloride is applied as the working desiccant. In the experimental study, instantaneous values of desiccant solution concentration is evaluated and recorded with time. Fig.11 demonstrates the principles of operation of the solar powered desiccant dehumidification system when a rotating wick is applied as a solar regenerator. In the proposed design, the regenerator comprises a rotating wick blackened surface which rotates between the upper and lower pulleys carrying the solution from tank and returns with regenerated solution. The strong regenerated solution leaves the collector and passes through a liquid column.

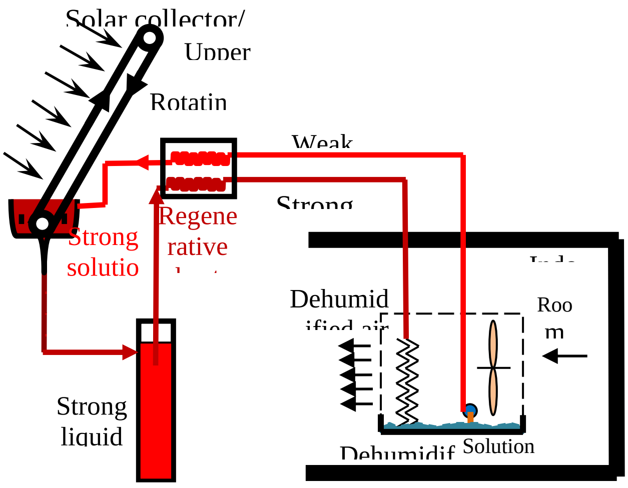

Fig. 11. Proposed solar desiccant dehumidifier using rotating wick [56]

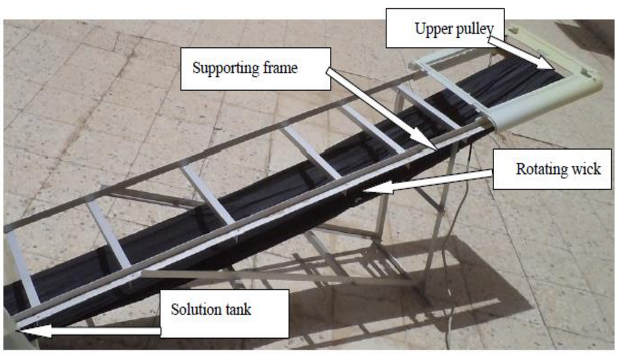

Fig. 12. View of the solar regenerator using rotating wick [56]

V. REGENERATION MODE

A liquid desiccant can be regenerated by either hot air or hot desiccant. Liu et al. [57] investigated the heat and mass transfer performances of these two regeneration methods. The result showed that the best mass transfer methods in hot air and a hot desiccant are parallel flow and counter-flow regenerator, respectively. The heat should be used for a desiccant in a packed bed regenerator because the performance of mass transfer for a hot desiccant regenerator is higher than that for a hot air regenerator.

5.1. Use of liquid desiccant with inert carrier

Hamed et al. [58] investigated theoretically and experimentally the performance of desiccant wheel in which lithium chloride is applied as the working desiccant.

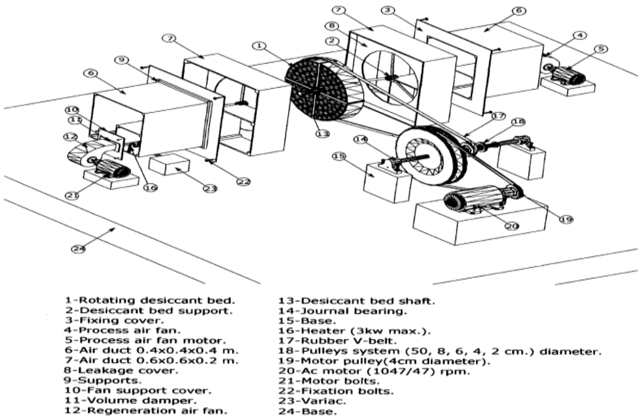

Fig.13. Schematic diagram of the experimental unit investigated by Hamed et al. [58]

The desiccant wheel has a cylindrical shape of 50 cm diameter and 10 cm thickness. The flow area of this bed is formed of 350 narrow slots, which are uniformly distributed over the cross section of the cylindrical bed. Each slot has a cylindrical shape and constructed from a steel spring of 100 mm length and 20 mm inside diameter (as shown in Fig. 13). To form the absorbing surface in the bed, each spring is coated with a thick cloth layer impregnated with lithium chloride solution, which is used as the working desiccant in these experiments.

A solar powered air conditioning system using liquid desiccant is proposed by Kabeel [59]. As shown in figure 14 solar air heater containing a porous material is used for regeneration purpose in the proposed system. The honeycomb desiccant rotary wheel is constructed from iron wire and clothes layer impregnated with calcium chloride solution, in honeycomb form, is utilized for the regeneration and absorption processes. The effect of airflow rate and solar radiation intensity on the system regeneration and absorption processes are studied. The obtained results show that the system is highly effective in the regeneration process. An empirical equation to calculate the removed moisture as a function of air flow rate at solar noon is obtained. Also empirical equation for wheel effectiveness as a function of air flow rate for regeneration and absorption process was obtained. It consists of a main duct being filled with a porous material (the aluminum foil).

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The porous material thickness is 0.005 m. Both sides and back are made of an iron sheet with thickness of 2 mm. The collector is inclined with an angle of 30º relative to the horizontal.

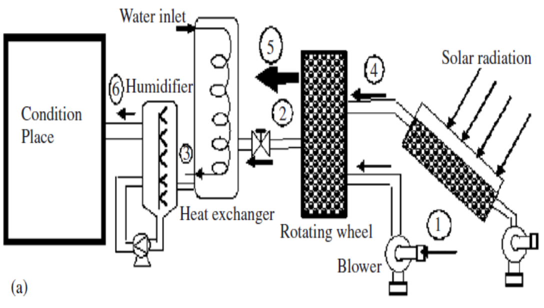

Fig. 14 Schematic of the solar powered rotating wheel desiccant system [59]

Rotating desiccant wheel using calcium chloride as the working desiccant is proposed by Hamed and Alosaimy [60]. The system is called desiccant operated humidity pump (DOHP). Mathematical model, which can be applied for analysis of the proposed system, is developed. The proposed system can be powered by low grade heat sources such as solar energy. Absorption-regeneration cycle for the DOHP is described and analyzed. An expression for the efficiency of the simple cycle is introduced. Theoretical analysis shows that strong and weak solution concentration limits play a decisive role in the value of cycle efficiency. System efficiency with consideration of heat and work added to the system is well defined. Dimensionless parameters defining the system design parameters are introduced. The limits of regeneration temperature and mass of strong solution per kg of produced vapor are found highly dependent on the operating concentration of desiccant. The basic concept of humidity pump is demonstrated in Fig.15.

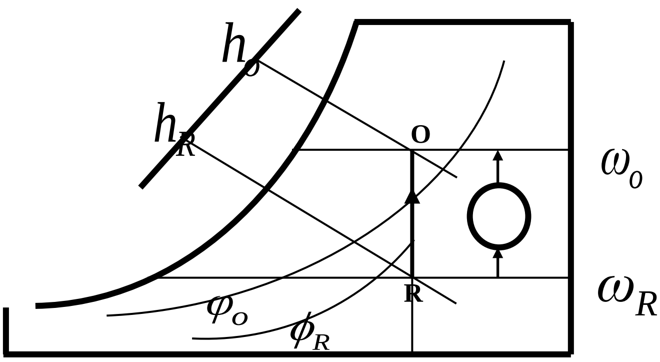

Fig. 15. The basic concept of Humidity pump

As shown in figure 15, air at the indoor conditions is dehumidified isothermally through the dehumidification process R-O, where the conditions R and O represent the room and outside conditions, respectively. The system which carries out this process is called a humidity pump (HP).

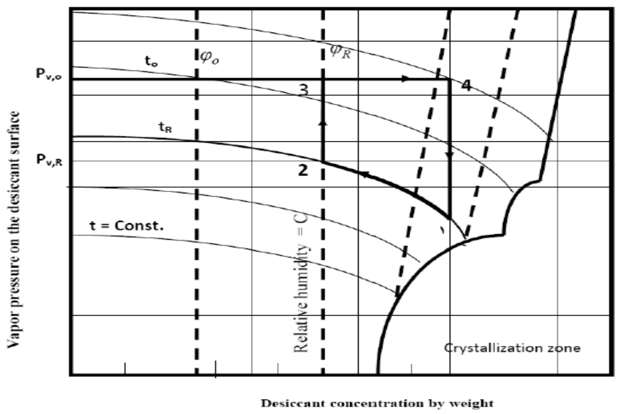

Fig. 16. Vapor pressure on the desiccant surface vs. desiccant concentration of the absorption-regeneration cycle [60].

However, isothermal absorption of water vapor from air can be carried out with continuous cooling of the desiccant during the process. At the end of absorption the desiccant must be regenerated to remove the absorbed water and re-concentrate the solution. The absorption-regeneration cycle, which can be applied, for operation as a humidity pump, is shown in Fig.16.

The theoretical cycle is plotted on the vapor pressure-concentration diagram for the operating absorbent and consists of four thermal processes which are [60]:

- Process 1-2: isothermal absorption of water vapor from room air;
- Process 2-3: constant concentration heating of the absorbent;
- Process 3-4: constant vapor pressure regeneration of absorbent and
- Process 4-1: constant concentration cooling of absorbent.

The configuration of the proposed system is demonstrated in Fig.17. As shown in figure it can be observed that the system is similar to the continuous absorption refrigeration system, and the absorber and regenerator in the present system deals with flowing air through rotating wheels. The lower section of the absorption rotating bed is immersed in the strong solution basin which functions as an absorber, where as the upper section of this bed, is subjected to the humid air at room condition to absorb water vapor from the room humid air.

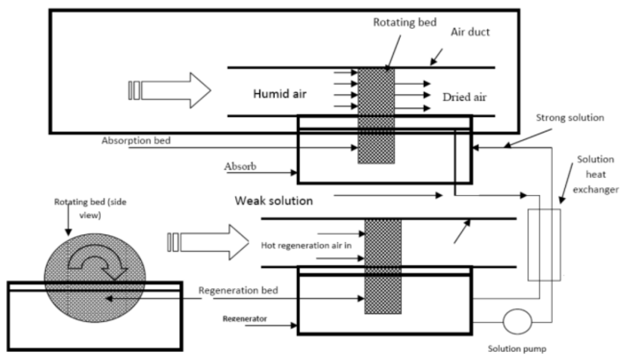

Fig. 17. Desiccant humidity pump [60].

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The absorption bed, which contains a porous material, rotates around its central axis and carries the solution from the lower section in the liquid side to the upper section in the air duct side. The weak solution resulting from the absorption process flows from the absorption basin to the regeneration basin, which is kept at the outdoor conditions. In the regenerator, the regeneration bed rotates and carries the solution from the regenerator to be heated and re-concentrated by the hot air through the air duct. Solution pump circulates the solution between the absorber and regenerator.

5.2. Transient Performance of packed porous bed impregnated with liquid desiccant

Grains of burned clay were used as a desiccant carrier to from the adsorption porous surface. The average diameter of used grains was about 9 mm. The grains were impregnated with Calcium Chloride solution with a concentration of 33.86% by submersion of dry grains in the liquid solution for a period of more than 24h. Porous grains impregnated with desiccant, are strained to remove the excessive liquid and avoid dropping of liquid from the bed. The mass of solution in the bed is then evaluated. By knowing the solution initial concentration and mass of solution in the bed, the mass of salt in the bed can be evaluated and assumed constant during experiments. The assumption used in the implementation of the simplified analytical solution is that the variation of solute concentration in the fluid with time is negligible compared with its variation in the adsorbent bed. The validity of this assumption can be proved by the results shown in Fig. 18, which illustrate the variation of humidity ratio of stream flowing through the bed for different layers. As shown in figure, the maximum change of air humidity is about 1 gm/kg air and occurs only at start of adsorption during a small period of time. Also, except for the first layer, the humidity is nearly constant for most of the adsorption period [61].

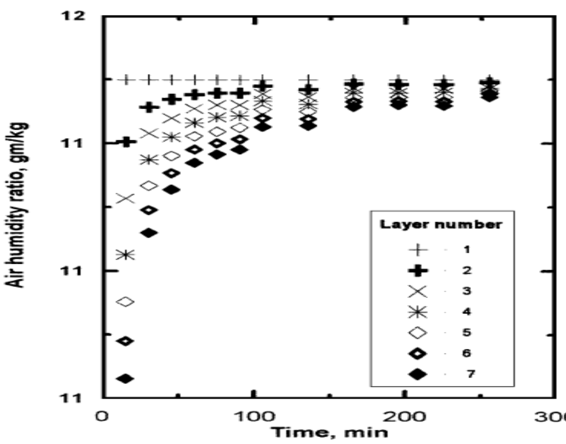

Fig. 18. Air inlet humidity ratio for different layers versus time [61].

The accumulated mass of water in the bed layers are presented in Fig. 19. As shown in figure, the higher value of mass of water is collected in the first layer. It is seen that the mass of water in different layers decreases with increase of height Z from the entrance of the bed. Also, when comparing any two adjacent layers, it can be found that the difference between the first and second layer is nearly higher than that between the second and the seventh layer. This means that rising the bed height will lower the mass of water absorbed per unit bed volume. Therefore, bed thickness is a design factor which must be properly selected.

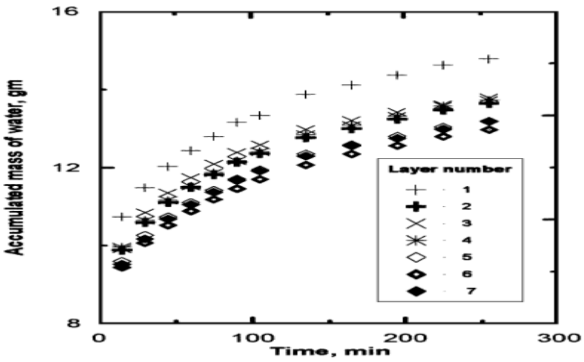

Fig.19. Accumulated mass of water versus time [61]

Transient variation of the rate of adsorption of water vapor for bed layers is presented in Fig. 20. It can be noticed that the adsorption rate decreases in an exponential nature. The maximum rate occurs at start of adsorption and its value depends on the initial concentration of desiccant in the bed. Transient values of solution concentration and vapor pressure on desiccant surface are shown in Figs. 21 and 22, respectively, for the two groups of experiments. Comparing the experimental results of Figs. 20 and 22, it can be observed that the rate of adsorption decreases with increase in vapor pressure on the desiccant surface. This because the potential for mass transfer process depends on the difference between vapor pressure in air stream (nearly constant) and that on the desiccant surface. This potential difference is also expressed as the difference between vapor concentration in air stream, and that value existing at equilibrium with solution in the bed.

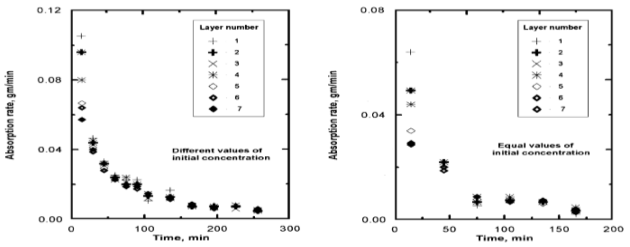

Fig. 20. Absorption rate versus time [61]

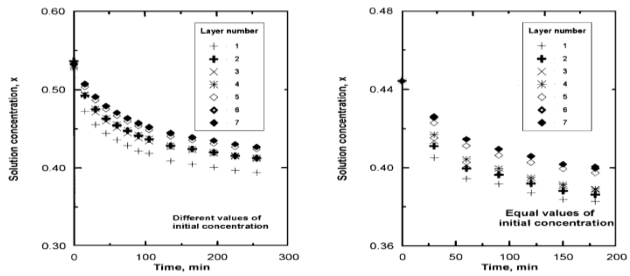

Fig. 21. Desiccant concentration versus time [61]

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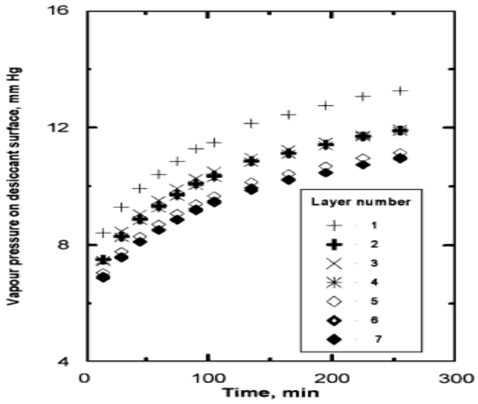

Fig. 22. Vapor pressure versus time [61]

From the analysis of experimental data, mass transfer efficient for the bed is potted with time as shown in Fig. 23. The average value of ka is about 0.52, which is presented by the solid line.

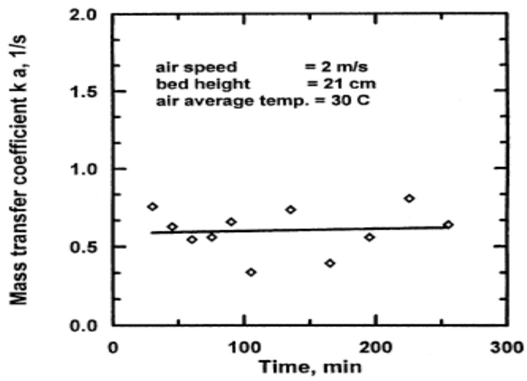

Fig. 23. Mass transfer coefficient versus time [61]

VI. ANALYSIS OF THE REGENERATION PROCESSES

6.1. Artificial neural network (ANN) models

Zeidan E et al.[62] presented a multiple-layer Artificial Neural Network (ANN) model to study the performance of a solar liquid-desiccant dehumidification/regeneration system. The experimental results of a previous study are used to construct the ANN model. Then the model has been tested and utilized to describe the effect of the inlet conditions of the air and liquid desiccant on the regeneration process. Good agreement between the outputs from the ANN model and the corresponding results from the experimental data has been found. The proposed model can work well as a predictive tool to complement the experiments. In this system, calcium chloride ($CaCl_2$) is applied as the working desiccant. They integrated the solar radiation model with the desiccant regenerator model to produce a more realistic simulation. The effect of the regenerator length, desiccant solution flow rate and concentration, and air flow rate, on the performance of the system is studied. They reported that the vapor pressure difference has a maximum value for a given regenerator length. Moreover, for specified operating conditions, a maximum value of the coefficient of performance occurs at a given range of air and solution flow rates. They recommended selecting the design parameters for each ambient condition to maximize the coefficient of performance of the system. In a second work by the same group, Aly et al. [63] investigated the performance of the same system but with the lithium chloride (LiCl) as an absorber. In [64] they also presented the modeling and simulation of the same previously described system with the input heat estimated via a real-time solar radiation model.

6.2. Heat and mass transfer between air and liquid desiccant

Cross-flow dehumidifier using LiCl liquid desiccant has been investigated experimentally by W.Z. Gao et al [65]. Effect of parameter of air and solution, as well as packing structure size, is examined to study performance and enhancement in dehumidification processes of air.

The schematic of the experimental setup is shown in Fig. 24, which consists of a liquid system, an air handling system and a water cooling system. The liquid desiccant system includes the solution tank, the pump, the heater, and the flow-meter. The air handling system consists of cooling coil, heater, humidifier and air rectifier channel. The water cooling system includes the heat exchanger and water valve. The liquid desiccant system and water cooling system are used to recover LiCl desiccant before it is introduced into the dehumidifier, and the previous set parameters of fresh air is handled by air handling system. Dehumidifier is the core device of the system, which is insulated during experiment. As shown in Fig. 25, Celdek structured packing is used for heat and mass transfer with large surface area density of 396 m^2/m^3 and flute height of 5 mm, and it consists of five layers of packing. Board with orifice, shown in Fig. 24, is set above the packing in order to get better solution distribution, and the board with different sizes of orifice is applied according to the solution flow.

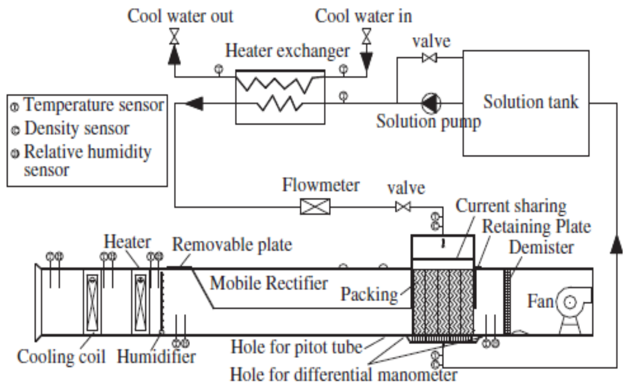

Fig. 24. Schematic of cross-flow liquid desiccant [65].

Mass transfer performance data of a cross-flow liquid desiccant dehumidification system using a structured packed tower. The structured packing consists of cross-corrugated cellulose paper sheets with a surface area per unit volume ratio of 608m^2/m^3. The liquid desiccant, viz. calcium chloride, flows through the pad from top to bottom, while the air flows horizontally making it a cross-flow configuration.

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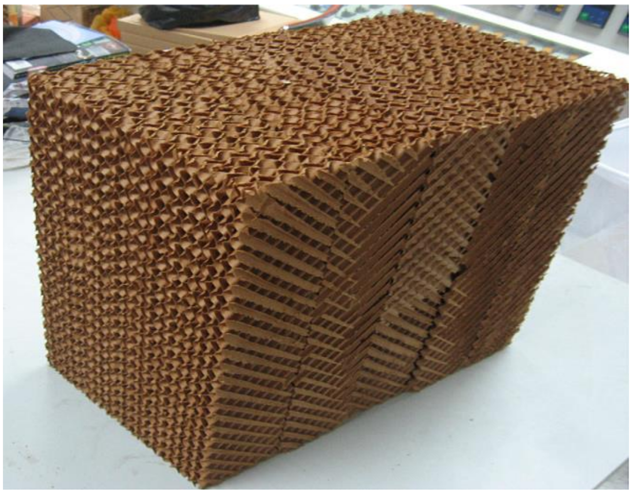

Fig. 25. Celdek packing for experiment [65]

Al-Farayedhi et al. [66] carried out a theoretical study on heat and mass coefficients in an air-desiccant contact system using a liquid desiccant. A gauze-type structured air dehumidifier was selected because it has good heat and mass transfer characteristics. The evaluated liquid desiccants were $CaCl_2$, LiBr, and a mixture of both solutions with a mass ratio of 1:1. Results showed that the mass transfer coefficient of the mixture solution is higher compared to a $CaCl_2$ solution. To verify the feasibility of the utilization of the hot air for the desiccant solution regeneration and disclose the performance of such kind of regenerators, performance analysis was conducted numerically by a validated mathematical model and parametric distribution of the air in a typical case was explored. The results showed that it was possible to use hot air for the desiccant solution regeneration when the requirement of the lowest inlet solution temperature was met and a typical case showed that the suggested hot air temperature was around 65 ◦C.

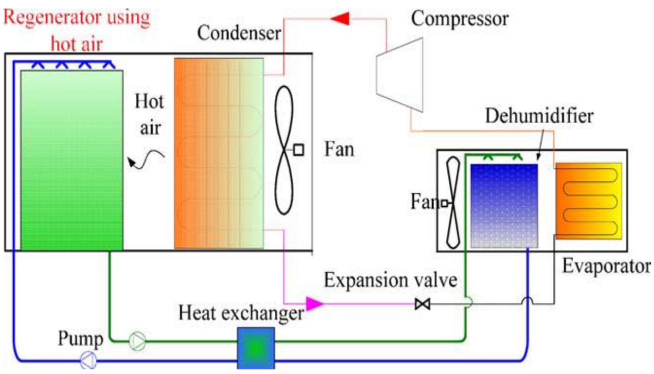

Fig. 26. An energy-efficient air conditioner with a desiccant solution regenerator using exhausted hot air from the condenser [67].

It is very valuable of this kind of regenerators to use waste heat from hot air in reality, such as exhaust air from condensers in vapor compression refrigeration systems, shown in Fig. 26, which is a hybrid system combining a vapor compression system with liquid desiccant dehumidification and regeneration. Such a system can succeed in obtaining high thermal performance and energy saving [67]. Therefore it is an energy-efficient system to use the hot air for the regenerator to recover waste heat from the hot air. Although the performance of the regenerator is not as good as the regenerator using the method of heating desiccant solution [68], the former can utilize the free heat from waste hot air.

An experimental work as a part of continuing investigation onto the concept and operation of an open cycle regenerative absorption cooling system has been conducted at the Faculty of Engineering, El-Mansoura University in Egypt by Sultan et al. [69]. The main objective was to study the effect of inlet parameters on the rate of evaporation of water vapor from the regenerated solution of CaCl2 as a liquid desiccant. The inlet parameters considered in the investigation are the inlet air temperature, solution flow rate, solution inlet concentration, airflow rate and humidity of inlet air. A packed tower for the regeneration of liquid desiccant is used. A total of 110 experimental data sets were taken under various operating conditions. From the results it was found that an increase of 360% air flow rate results in 11% increase in the solution output temperature. The authors concluded that the regeneration process is highly dependent on the air inlet temperature, humidity, and flow rate. Zhang L et al. [70] studied mass-transfer characteristics of a structured packing dehumidifier/regenerator using a lithium chloride solution as the desiccant. Experiments included air dehumidification and desiccant regeneration in typical operating ranges of air-conditioning applications. When the air velocity increased from 0.5 to 1.5 m/s, the overall mass-transfer coefficient in the structured packing dehumidifier and regenerator varied from 4.0 to 8.5 g/m2 s and from 2.0 to 4.5 g/m2 s, respectively. Higher solution temperature resulted in lower overall mass-transfer coefficients. Dimensionless overall mass-transfer coefficient correlations were developed for the dehumidifier and regenerator.

Longo and Gasparella [71] presented the experimental tests on desiccant regeneration carried out in a packed column with the hygroscopic solution H_2O/LiBr. Two different packed columns have been tested. The experimental results are reported in terms of desiccant concentration increase, regeneration effectiveness and air side pressure drop. The experimental tests show that desiccant regeneration requires a temperature level around 50 ºC that can be easily obtained by using solar energy or heat recovered from an industrial process or from a thermal engine. The experimental rig (see Fig. 27), consists of an air line and a desiccant loop. In the first loop ambient air is heated and humidified to achieve the set conditions at the inlet of the packed column. The air goes through the packed column, where the heat and mass transfer takes place in a counter-flow configuration (air up-flow and desiccant down-flow) and is then discharged. An air dehumidification process or a desiccant regeneration process occurs depending on the relative values of the partial vapor pressure on the air and desiccant side.

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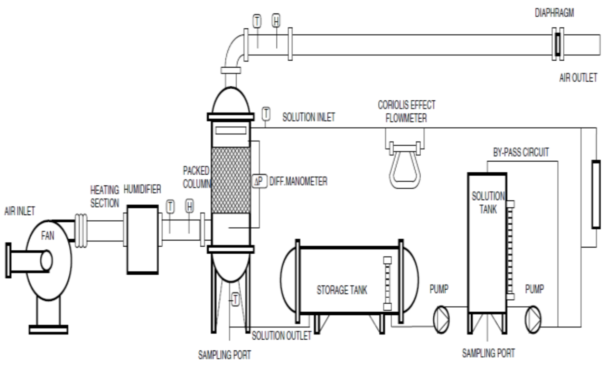
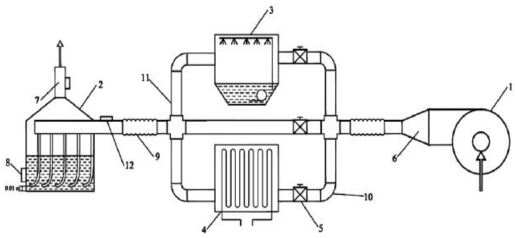


Fig. 27. Schematic view of experimental test rig [71].

6.3. Processes using an injected air through the liquid desiccant solution

An experimental study was carried out by Kabeel [72] to evaluate the liquid desiccant system performance during dehumidification and humidification processes using an injected air through the liquid desiccant solution (calcium chloride). A different air mass flow rates though the desiccant solution was considered during the experimental work. The desiccant system was studied at different operating conditions like different temperatures, different humidity ratios and different solution levels. The effectiveness for both the dehumidification and humidification processes was calculated through this work. It was found that, the system effectiveness reached to 0.87 in the dehumidification and about 0.92 in the humidification process. As shown in Fig. 28, solution tank contained the desiccant solution is mounted. A mechanical blower is used to inject the external air through the solution tank with different air mass flow rates. A fan is used to pass an outside air to a three different paths, where only a one path can be used during the experimental work. The first outside air path is directed to the solution. The second air path is directed to the humidifier to control the humidity of the air before the injection into the solution. The third air path passes over an electric heater to rise the air temperature before the injection into the solution. During the experiment, one of the paths is used while the others are closed by using a valve arrangement. The dimension of all ducts used for the three paths have 0.05 m internal diameter. The air is injected through a series of pipes where ten pipes are used to obtain homogonous distribution. The liquid desiccant used in this work has an initial concentration of 40% at different levels in the solution tank. A small air-washer is applied for this work to control the air inlet humidity.



1- blower	5-three valves	9- flexible joints
2- solution tank	6- inlet air sensor	10- four 90 elbows
3-air washer	7- exit air sensor	11- rigid pipes
4-Electric heater	8- solution sampling	12- thermostat

Fig.28 Experimental set up for dehumidification and humidification processes using an injected air through the liquid desiccant [72]

VII. PERFORMANCE IMPROVEMENT OF LIQUID DESICCANT AIR DEHUMIDIFIER SYSTEM

Bakhtiar A et al. [73] proposed a method to evaluate the performance of liquid desiccant air dehumidification system. In their method, the total load energy change is compared with the total energy consumptions during the desiccant exchange period. They performed an experimental study to verify their method. This experiment is just focused on evaluating the performance of dehumidifier system therefore there is an isolated room connected to the dehumidifier side. The schematic diagram of the complete system is shown in Fig. 29.

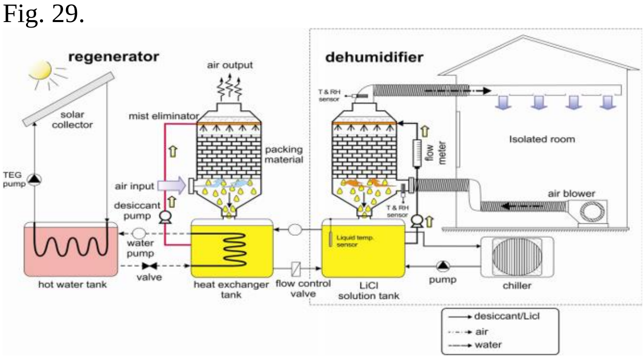
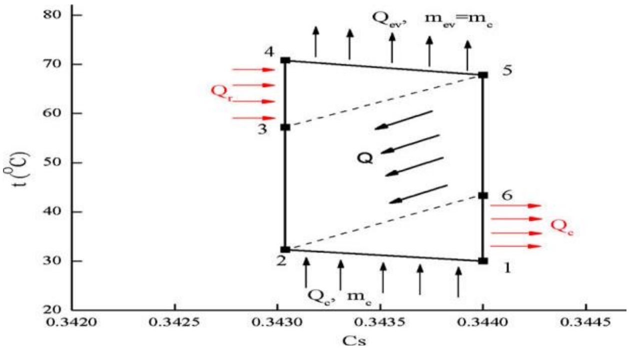


Fig.29. Schematic diagram of the complete system [73]

This system consists mainly of two cross flow air-liquid desiccant contacting surfaces named dehumidifier and regenerator.

7.1 Two-stage liquid desiccant dehumidification system

Xiong et al.[74] developed a two-stage liquid desiccant dehumidification system assisted by calcium chloride ($CaCl_2$) solution through exergy analysis based on the second thermodynamic law. Compared with the basic liquid desiccant dehumidification system, the proposed system is improved by two ways, i.e. increasing the concentration variance and the pre-dehumidification of $CaCl_2$. The exergy loss in the desiccant–desiccant heat recovery process can be significantly reduced by increasing desiccant concentration variance between strong desiccant solution after regeneration and weak desiccant solution after dehumidification. Compared to the basic system, the thermal coefficient performance and exergy efficiency of the proposed system are increased from 0.24 to 0.73 and from 6.8% to 23.0%, respectively, under the given conditions. Useful energy storage capacity of CaCl2 solution and LiCl solution at concentration of 40% reach 237.8 and 395.1 MJ/m^3, respectively. The effects of desiccant regeneration temperature, air mass flux, desiccant mass flux, etc., on the performance of the proposed system are also analyzed. A basic liquid desiccant dehumidification system is depicted in Fig. 30 (a, b), as well as its desiccant solution cycle. The system is composed of a dehumidifier, regenerator, and several heat exchangers. Its working principle was well described in the Ref. [74].

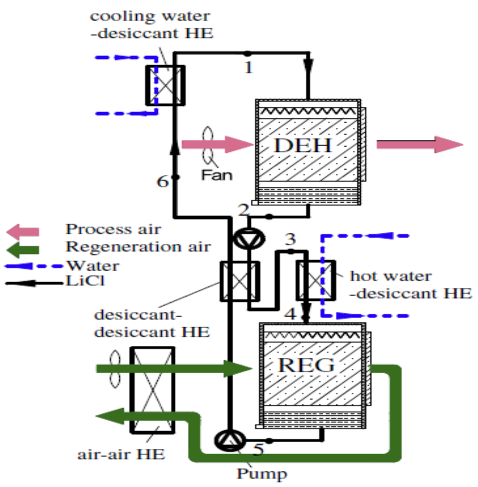


(b) Liquid desiccant cycle

Fig. 30. (a) , (b) The basic liquid desiccant cooling system (DEH: dehumidifier; HE: heat exchanger; REG: regenerator) [74].

7.2. Solar-powered liquid desiccant system to supply building fresh water and cooling needs

Audah et al. [75] studied the feasibility of using a solar-powered liquid desiccant system to meet both needs the production of fresh water and space environmental comfort at minimum cost. It is found in the case study that the heat sink temperature is a critical optimization parameter and dictates the appropriate regeneration temperature within the constraints of operation of the system to deliver its outputs of fresh water and dry cool air stream. Fig. 31 depicts the solar-powered liquid desiccant system and condensing unit. The system is composed of a dehumidifier, regenerator, parabolic solar collectors, heat exchangers, and desiccant cooler. The air leaving the desiccant bed is used for household air conditioning. The liquid desiccant leaving the dehumidifier enters a heat exchanger where it is warmed up. It is further heated before entering the regenerator by another exchanger in the water storage tank heated indirectly by solar energy transmitted from the concentrators' closed fluid circuit. The hot low concentration liquid desiccant enters the regenerator where counter flow ambient air absorbs the water accumulated from the desiccant.



(a) Schematic

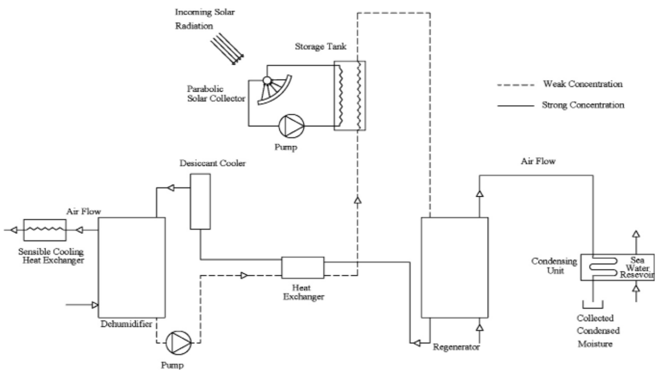


Fig. 31. Schematic of the liquid desiccant system [75].

VIII. CONCLUSIONS

A detailed literature survey of different liquid-desiccant solar regeneration technologies was performed. It is understood from the review that new configurations of the solar regenerator are highly welcome to maximize its benefits. Desiccant applications, such as recovery of water from air, integrated with solar cooling systems increase the system availability and improve the overall performance. The possibility of replacing the mass exchange equipments (absorber and regenerator) by evaporative coolers can be planed for future studies.

IX. ACKNOWLEDGEMENT

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