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A Review of Experimental and Numerical Evaluations of Solar-Powered Liquid Desiccant Dehumidification Systems

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Abstract: A review of the literature focusing on the latest developments in liquid desiccant air dehumidification, with an emphasis on component, system, and material manipulation techniques, is also included in this study. It takes a lot of energy to regulate indoor humidity, particularly in tropical and subtropical nations. The air supplied to the system can be dried in a single step by using a liquid desiccant for dehumidification. Energy storage, high-quality air, low-grade thermal energy, and humidity control are some of the benefits of this technology. As with the recent decades developed, this technology and in recent decades this technology has been modified and its limitations have been studied on a large scale. However, several issues still exist, primarily due to the use of a corrosive desiccant with a limited heat capacity and insufficient wettability on the packing column. The aforementioned research outlines the challenges that come up when using a desiccant, including large heat loads, inadequate wetting, a tiny contact area of liquids and air, an ineffective solution of droplet loading, and a large amplitude of temperature in heat/mass transfer. After that, optimization techniques are assessed to enhance the system's functionality and viability in these three domains. Optimization of the system using a heat pump, vapor compression device, solar collector, or waste heat recovery materials, such as desiccant materials, packaging/panel surfaces, or honeycomb paper, a new type of vacuum regenerator, electrolysis, or a hollow fiber membrane dehumidifier. This review will help identify research gaps and identify contemporary methods to improve the practicality of removing moisture from the air using a liquid desiccant.

Keywords: Dehumidification, Liquid desiccant, Solar heat regeneration, Powered solar system

Introduction

Global energy demand has increased significantly over the last several years and is expected to increase by 50% by 2050 (Vivekh et al., 2023; Chen et al., 2020). Fossil fuels, whose supply is limited and whose usage affects both the environment and human health, are a more conventional method of supplying this energy demand. To mitigate these adverse consequences, research is also being done on the usage of non-renewable sources that impact the rising energy demand (Demirbaş, 2001;Homod et al., 2021). The nation should rely less on non-renewable energy sources like gas, coal, oil, etc. for long-term energy security.

A stronger preference for the effective use of renewable energy sources (Tang et al., 2018; Liu et al., 2022). It is becoming more and more clear that sustainable economic development requires renewable energy in all of its forms (Abdelrazik et al., 2022; Iqbal et al., 2023; IRENA, 2020; Lefebvre & Tezel, 2017) (Figure 1). illustrates the 2050 global energy shift. Pakistan's energy needs for both residential and industrial uses are rapidly increasing, much like those of other nations. Fossil fuels are being used to meet most of the demand. This has detrimental effects on human health and the environment in addition to reducing the nation's supply of fossil fuels and creating a severe energy shortfall.

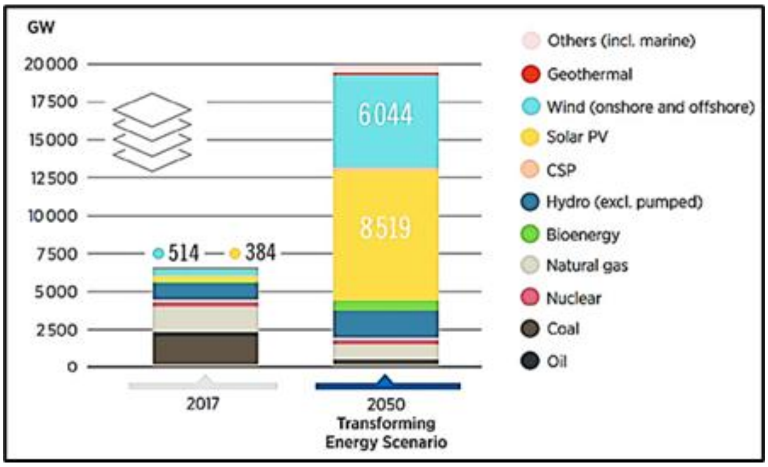

Figure 1. Scenario for global energy transition by 2050 (International Renewable Energy Agency, 2017) (Lefebvre & Tezel, 2017).

Additionally, ventilation systems are seen as essential to society and are used on a daily basis. The vapor compression refrigeration system (VCRS) technology, which has been around for 190 years despite various modifications, is used in most air conditioning systems. Nevertheless, the VCR's primary drawbacks are its enormous power consumption and use of extremely harmful refrigerants. Energy conservation and environmental protection are top priorities in the twenty-first century. More focus is being placed on finding alternative refrigeration systems that are less energy-intensive and environmentally friendly in order to address these issues. The liquid desiccant systems are becoming favorable for use because they use less energy and are environmentally friendly (Naveen & Kolakoti, 2024;Ghoulem et al., 2019).

Design and Construction

This is due to the fact that the primary purpose of cooling a liquid drier system is to maintain consistent temperatures during the dehumidification process. It is important to realize that a wide variety of structures and formations can be created in order to achieve this goal. One problem is adding internal cooling. However, it adds a heat component to the procedure. Depending on their construction and design, internally cooled dehumidifiers can be divided into the following categories.

Operating Dehumidifiers from Packed Beds

These are packed towers structured with internally placed tubes conveying the refrigerant, as illustrated in (Figure 2) . which were selected from (Qiu et al., 2012) focusing on experiments using structured packed tower dehumidifiers and the comparison between adiabatic and internally cooled ab sorbers in cross flow of an aqueous solution of calcium chloride ($CaCl_2$) and reported that internally cooled showed better perspective. Gommed et al. (2015), the authors carried out an empirical investigation of an intern-cooled and extern-cooled air-cooled condenser with the structured packed beds of HDPE and titanium tubes for internal cooling. Recently, Jia et al. (2007) performed a heat and mass transfer coefficient evaluation of the water-filled tube towers for internal cooling through a mathematical model. This performance is benchmarked against the parallel plate system layout shown in (Figure 3) and the finned coil system layout shown in (Figure 4).

The overall efficiency of the three systems is depicted by the results presented herein whereby the packed tower systems recorded the lowest efficiency while the fin tube system recorded the highest efficiency. Another work by Liu et al. (2016) and Taherian et al. (2009). Provides an experimental investigation to evaluate the rate of moisture removal. and dehumidification efficiency of a desiccant dehumidifier with an interior cooling packed tower. In their experiment, as pointed out in the study explained above, TEG was employed as a desiccant liquid.

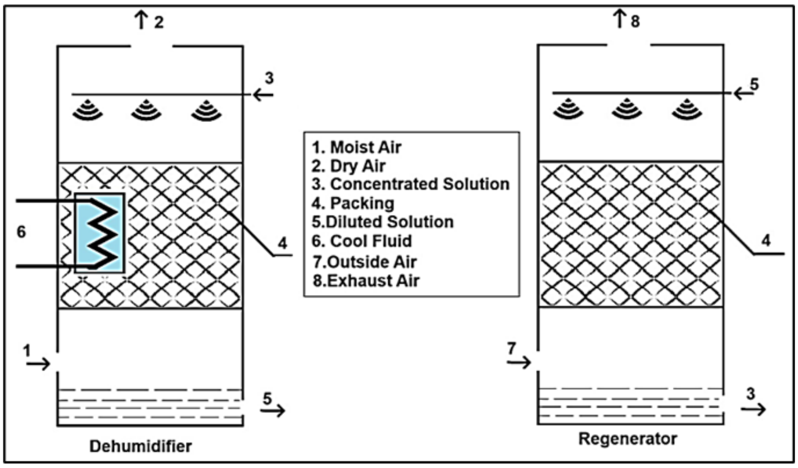

Figure 2. Packed bed dehumidifier with intercooling without intercooling(Qiu et al., 2012; Gommed et al., 2015).

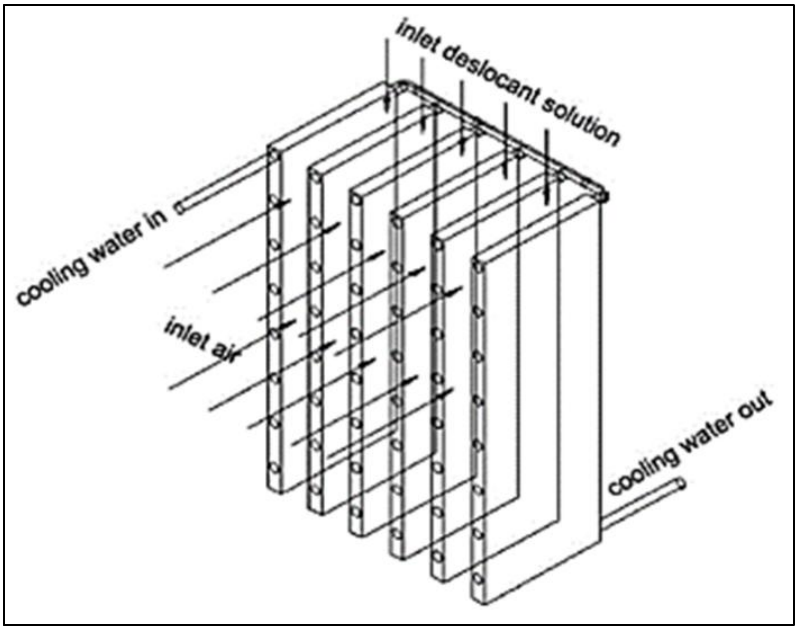

Figure 3. Internally cooled parallel-plate packing material dehumidifier(Jia et al., 2007; Rambhad & Walke, 2018)

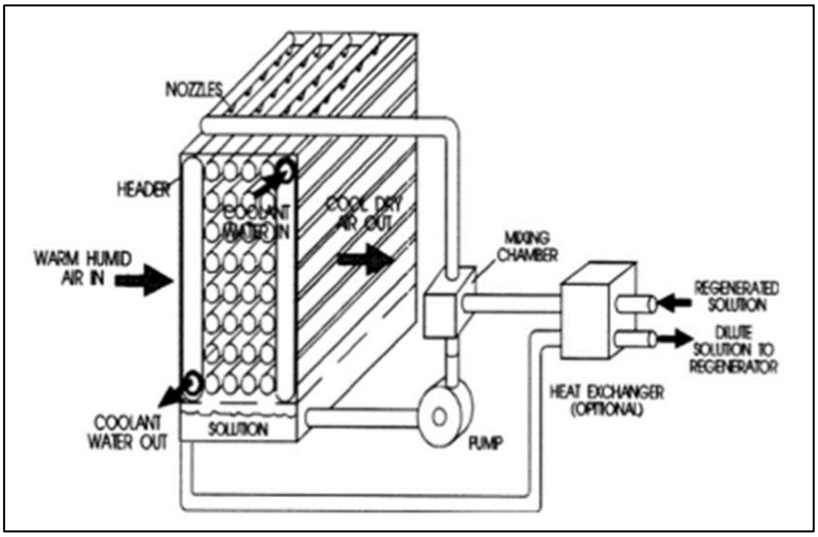

Figure 4. Finned tube dehumidifier that is internally cooled(Gommed et al., 2015;Jia et al., 2007)

Liquid Desiccant Dehumidification System

Figure 5 shows it primaly extends a water bath, two heat exchangers, fans, a regenerator, a heater, a cross-flow desiccant dehumidifier, etc. Concerning the dehumidifier's interacting liquid desiccant solution, it is directed to fall downward and cascade along the inner face of the honeycomb wall; as for the honeycomb wall's outer face, it can use the sprinkler to distribute the liquid desiccant in a thin layer. The specification of honeycomb paper is explained in (Figure 6) below: It is porous, non-shrinkable due to rewetting and drying cycles, and contains more surface area per unit volume of packing. In the dehumidifiers and the regenerator, the utilization of two honeycomb papers with two different wave angles, for instance 450 and 600 is used. These sheets are oriented in parallel to each other and thus are shifted opposite to one another to provide an air channel that will further improve the mass transfer. Initially, a fan draws process air through the duct where air humidity is adsorbed, while both air and liquid desiccant become hot owing to the heat generated by the mixing process of eliminating moisture from the air. Liquid drying solution is also diluted during this process and needs to be regenerated by making up the moisture-removing cycle. The regeneration process is concluded by way of a new heater and generator. The diluted solution is heated in the heater using either sunshine or an extra source, and the generated heat is used to supply the generator where fan airflow removes the absorbed humidity. The solution is then concentrated and goes back to the dehumidifier after having been cooled by the water bath. Thus, a constant dehumanizing cycle is established (Wang et al., 2022; Lowenstein et al., 2006).

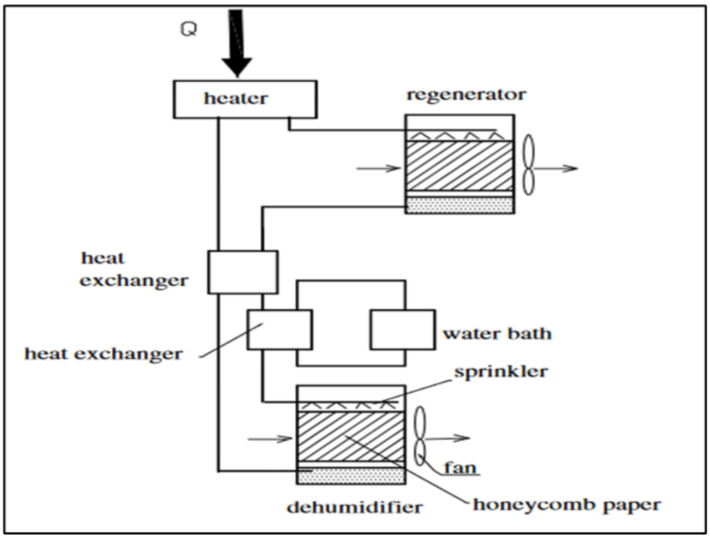

Figure 5. Schematic of a moisture removal system using a liquid desiccant (Wang et al., 2022;Lowenstein et al., 2006)

Dehumidification Devices for Panels

Another type of internals-cooled dehumidifier is the parallel plate absorber that encourages the provision of internals cooling. These should be meant for air, cooling fluid, or solution to accommodate a large surface area for cooling. The solution used in this process has to first fall over the plates through the force of gravity and what you get is a film over the surface of the plate as shown (Dong et al., 2022; Li et al., 2023) developed and built a parallel plate dehumidifier in which the air and solution flow opposite to one another in the contact zone and the other zones pumping water and airflow in opposite directions, the cooling is by regeneration by evaporative cooling Abene et al. (2004) and David et al. (2021) comprehensively experimented as well as numerically examined a cross-flow plate system in which process air solution and return air cooling water are carried via any two plate passageways to cool the plates internally by indirect evaporative cooling. As can be observed in (Figure 7) both the liquids are sprayed (Mesquita et al., 2006). According to the study, additional research is required to support the hypotheses provided in this (publication and enhance alignment with other relevant studies (Jamal-Abad et al., 2016;Iqbal et al., 2023) used three distinct approaches to propose parallel plate air dryers with internal cooling using mathematical models. The first one is associated with the heat and mass transfer coefficients: the second one is the coefficient resulting from the energy, momentum, and diffusion equations and the types going with the momentum diffusion, thermal diffusion, and mass diffusion respectively. However, an insignificant account is taken on the solution layer thickness variation due to moisture transport and the third one is similar to the second one but modifies the solution layer thickness variation parameter for obtaining better accuracy of the solution. In all methods, a fully developed laminar flow assumption was employed in the computational simulation (Mehare et al., 2025; Fumo, 2002).

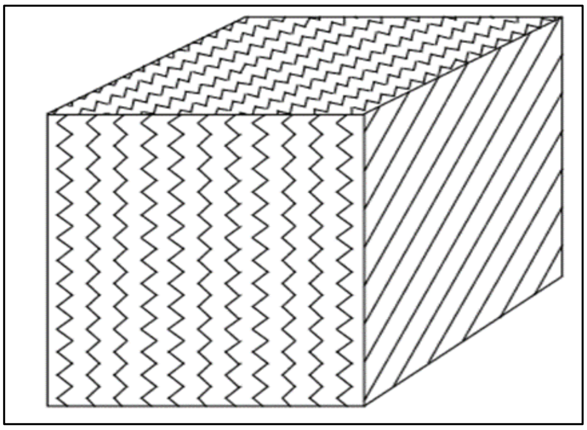

Figure 6**.** Honeycomb paper as packaging material (Abene et al., 2004;Li et al., 2023)

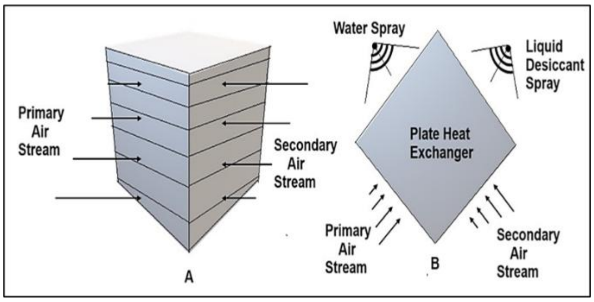

Figure 7**.** Tablet dehumidifier (Abene et al., 2004;David et al., 2021).

Solar-Assist Dessiccant Déshumidification System

The flat plate solar dryer-assisted dehumidification system's experimental setup is depicted in Figure 8 (Gurubalan et al., 2019; Algarni et al., 2018). The SADDS included a sun dryer and a rotary dehumidifier. The rotary dryer wheel is a cylindrical wheel that is placed aside to rotate while the drying process is underway. Silica gel is packed inside the wheel to draw moisture from the process air. Figures 9 and 10 show the dryer wheel, which had a honeycombed construction and was permeable to air. As seen in the diagram below, there are two rectangular ducts fixed on either side of the dryer wheel.

The duct's purpose was to guarantee appropriate airstreams from the regeneration portion and the procedure. Both the process and the regeneration tracks are supplied with air by two variable frequency air blowers. A moisture-retaining substance (silica gel) is used to collect moisture from the air on the revolving wheel's operation side. Thus, by removing moisture in a dryer wheel with significant water absorption capacity, it is feasible to achieve the required relative humidity in the air. As a result, the dehumidification process may cause the entire wheel to become humidified, necessitating a regeneration stage in which hot, dry air is used to continue the dehumidification process. Therefore, the drier material (silica gel) was regenerated using hot air supplied by the flat plate solar air collector (FPSAC) at the dryer system's regeneration side intake. FPSAC is manufactured in a laboratory equipment manufacturing facility. The collector receives solar radiation from the sun, and the air moving over it is heated by the collector's highly heat-absorbing substance.

An insulating layer of aluminum foil is applied over the collector to speed up heat transfer between the absorber and the air and reduce thermal losses. To minimize volumetric flow rate losses, the air blower is positioned upstream of the FPSAC's exit and in front of the regeneration side's inlet. Through the regeneration side intake, hot air is extracted from the solar collector and discharged. In SADDS, the flow patterns of the regeneration air are reversed. Additional electric heating is employed at night and/or during cloud cover as part of the regeneration process. Tables 1 and 2 provide an overview of the dryer rotary wheel and FPSAC technical features (Gurubalan et al., 2019; Algarni et al., 2018).

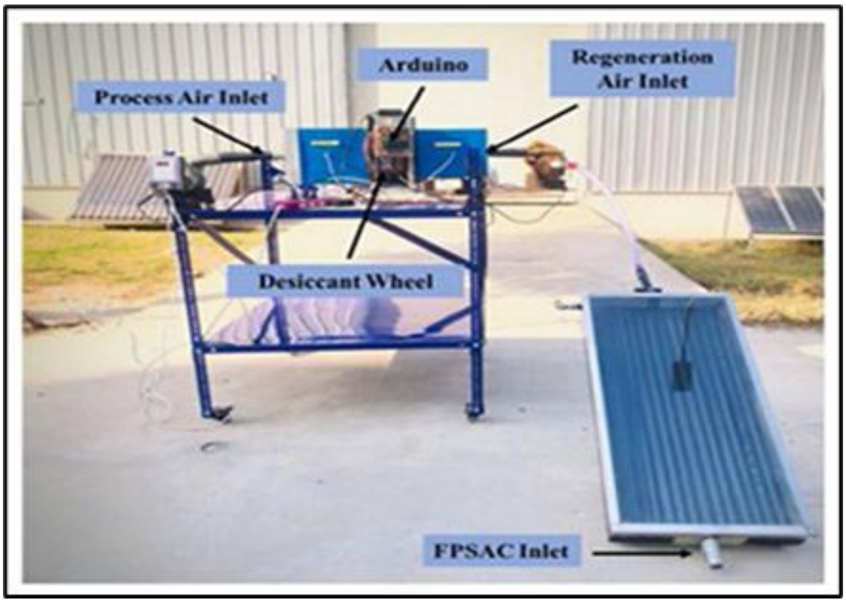

Figure 8. Desiccant dehumidification system assisted by solar power (SADDS). (Gurubalan et al., 2019; Algarni et al., 2018)

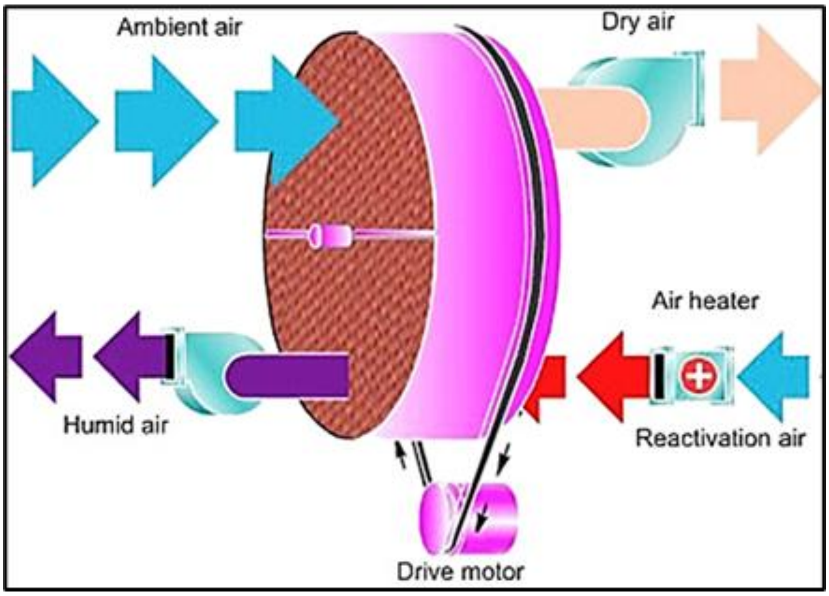

Figure 9. The interior of a desiccant wheel. (Gurubalan et al., 2019;Algarni et al., 2018)

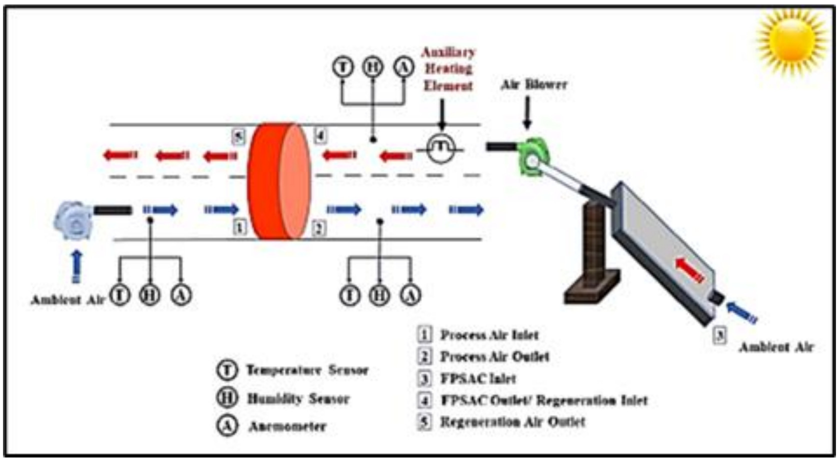

Figure 10. Diagrammatic representation of the desiccant dehumidification system with FPSAC assistance (Gurubalan et al., 2019;Algarni et al., 2018)

Table 1. Technical details of rotary dryer wheel. (Gurubalan et al., 2019;Algarni et al., 2018)

Variable	Measured property	Property value
Desiccant wheel	Rph	104 rev./h
	(Rated power Hight)	3.75 W
	Diameter of wheel	254 mm
	Depth of wheel	146 mm
	Cassette length/height	350 mm
	Process/Regeneration side area	10067.28 mm^2
Rectangular duct	Ducts number	4
	Each duct area	247 mm
Process side fan	Rated power	600 W
	Rated flow rate	168 m^3/h
Regeneration side fan	Rated power	600w
	Rated flow rate	210 m^3/h
Auxiliary electric heater	Electric rods number	1
	Rod rated power	400 W

Table 2. FPSAC technical specifications (Gurubalan et al., 2019;Algarni et al., 2018)

FPSAC mesured variable	**Variable value**
Length	1036 mm
Height	122 mm
Width	548 mm
Collector area	0-567
Angle of tilt	30^o
Angle of azimuth	9-10^o Southwest
Glazing thickness	5 mm
Latitude	33.73
Longitude	73.08

Recent Advances in Liquid Desiccant

These are heavy-duty fluid desiccant materials that principally comprise the main features of the total dryer cooling system. For this reason, the author considered it useful to discuss the properties of liquid desiccant to determine the best candidates to use in the system. Identified liquid desiccant material is of two categories; 1 Organic liquid desiccant materials: Organic solvent solutions are Triethylene glycol (TEG) aqueous solutions, diethylene glycol, and ethylene glycol 2Inorganic liquid desiccant materials:

Table 3. Experimental vapor pressure for aqueous salt solutions (Murthy et al., 2020).

Salt type	Concn.(%)	Vapor pressure (kPa) of aqueous 298.15 ^{o}K	303.15 ^{o}K	308.15 ^{o}K	313.15 ^{o}K
LiCl	30		2.2		2.79
	38		1.79		2.41
	40	1.48	1.79	2.13	2.41
	44		1.47		2.1
LiBr	31		3.11		3.67
	37		2.9		3.47
	40	2.45	2.85	3.08	3.35
	44		2.57		3.14
$CaCl_2$	32		2.78		3.36
	37		2.55		3.13
	40	2.1	2.53	2.36	3.14
	43		2.2		2.8

These are inorganic salt solutions include $CaCl_2$, lithium chloride (LiCl), lithium bromide (LiBr), and calcium bromide (CaBr2) (Su et al., 2022;Abdul-Wahab et al., 2004). TEG solution has found application for cooling in a solar-powered liquid dryer as reported by Liu et al. (2011) and Conde (2004). However, the experiment confirms that TEG has high efficiency for refrigeration systems as a desiccant, but due to the TEG boiling point being very close to water, TEG may evaporate in the treated air.

Consequently, the issue of liquid transmission places TEG out of bounds for liquid dryer cooling applications. Highly efficient and popular fluids for fluid drying systems are solutions of inorganic salts, namely $CaCl_2$, LiCl, LiBr, and potassium formate. The efficacy of the dehumidification process of a desiccant depends primarily on the vapor pressure of the desiccant. Thus, the differential pressure that drives moisture absorption in a regenerator or a dehumidifier is as follows: partial pressure of airborne water minus vapor pressure of water above the desiccant solution (Conde, 2004). The lower the inlet steam pressure to this parameter; the higher the state of dryness of the air leaving the dryer, and therefore better dryer performance. In the following experiments, the vapor pressures of LiCl, $CaCl_2$, and LiBr at the temperature conditions given in the (Table 3) (Murthy et al., 2020) below were measured.

Solutions of Halide Salts

The organic component was TEG. However, owing of its high viscosity and potential for unstable operation due to its remain in the liquid, its use is restricted. According to Guo et al. (2019) and Elsarrag (2006), glycol's low surface vapor pressure makes it volatile. Glycol is therefore unsuitable for use in air conditioning systems as losses of glycol in the conditioned Space's instability might double the expense of the system. Furthermore, by applying 42% LiCl, Oladosu et al. (2023) and Rafique et al. (2016) discovered encouraging results that correlated the air dew point with 96% TEG, emphasizing that the molar concentration of glycol in the air must be one in a thousand concentrations of water vapor. As a result, there will be a significant annual loss of triethylene. LiCl, CaCl2, and LiBr are a few of the most often used salt halide desiccant solutions these days (Gao et al., 2014 ;Zuber et al., 2013; Liu et al., 2019; Chen et al., 2020;Wen et al., 2018 ;Henning, 2007) evaluated the water vapor pressure and concentration of the different desiccants. These demonstrated that LiCl solution, which has the lowest vapor pressure and a drying capacity of 30–40%, is the most efficient liquid desiccator among the investigated halide salts. Unfortunately, the expense of LiCl makes this approach expensive. Systems that employ LiCl solution as a liquid desiccant have been studied for their capacity to dehumidify and regenerate (Varela et al., 2018; Zhang, 2011; Chuanshuai et al., 2016; Zhang et al., 2012; Qi et al., 2019b; Fumo, 2002). Chen et al. (2015) examined a dryer cooling system driven by a heat pump using LiCl solution as a desiccant (Qi et al., 2019a). The maximum recorded temperature drop was 5.2–7.4°C, the average COP was 4.0, and the temperature and humidity of the inflow air were found to be 25.4–27.8°C and 13.9–18.2 g/kg, respectively. CaCl2 solution is the most widely used and reasonably priced desiccant, however it is unstable and depends on the concentration rate and inlet air conditions. Heat and mass transfer in a cross-flow dryer with a calcium liquid dryer system at 40% of the concentration of CaCl2 solution was practically assessed by (Chuanshuai et al., 2018) (Mohammad et al., 2014). A theoretical comparison of the mass transfer performance of LiBr and CaCl2 solutions was conducted by Chuanshuai et al. (2019) and Naik et al. (2020). The author came to the conclusion that LiBr carried out heat and mass transfer more effectively at the same temperature and crystallization temperature as the CaCl2 solution. Magnesium chloride (MgCl2) was employed as the desiccant solution to solve crystallization problems in a liquid-to-air membrane energy exchanger (Guan et al., 2020; Namvar et al., 2012). All of the experiment's results showed that crystallization had not occurred since the average MgCl2 content had not reached the saturation concentration, which ranged from 35.9%. Aqueous LiBr performs similarly to LiCl during dehumidification and regeneration, but being 20% more costly. In one experiment, the mass transfer performance of LiCl LiBr was examined at an air mass flow rate of 0.24–0.48 kg/s and an input air temperature of 25.4–38.8 °C (Rafique et al., 2016; Liang et al., 2019). The COP of the two desiccant liquid dryer refrigeration systems is near LiBr 0.45 and LiCl 0.47, according to the authors of the two publications. A mathematical model of an adiabatic counterflow desiccant dehumidifier created by la et al. (2010) can forecast the system's adsorption efficiency. LiCl, LiBr, and CaCl2 were found to have adsorption efficiencies of 0.145, 0.137, and 0.125, respectively. After examining numerous measured data from the literature, Conde (2004) and Jain et al. (2011) developed a set of interpolation equations for the solubility limits, vapor pressure, density, surface tension, dynamic viscosity, and differential heat of dilution of CaCl2 and LiCl. As a result, they can serve as a reference when creating a computer-aided liquid dryer refrigeration system design. Because certain empirical representations lack great precision, it is preliminary. Gandhidasan and Mohandes (2008), Wen et al. (2018) employed the artificial neural network (ANN) approach to forecast a wide range of vapor pressures of CaCl2, LiCl, and LiBr. The outcomes of the LiCl and LiBr validation correspond reasonably well to the data available from the literature. We were also able to study other forms of halide salts (Chuanshuai et al., 2018; Elmer et al., 2016) for a liquid desiccant system, used $MgCl_2$ as a desiccant and the working concentration of $MgCl_2$ was lower than the saturation concentration (35.9%) so the crystallization problem can be avoided.

Ionic Liquids and Organic Acids

The three salts listed above have the disadvantage of being corrosive, which can cause major damage to the air conditioning system. Potassium formate (KCOOH) solution is more environmentally friendly due to its lower corrosiveness. was recently utilized in a refrigerated desiccant unit, among other facilities. KCHOOH solution is noncorrosive, nonvolatile, and has low toxicity and viscosity. This approach is straightforward, efficient, affordable, and eco-friendly because KCHOOH is miscible with water (Longo & Gasparella, 2005; Shukla & Modi, 2022).

Additionally, potassium formate can outperform the existing liquid desiccants at high solution concentrations by increasing the magnitude of the sharp vapor pressure drop and the crystallization temperature of less than 273 K (Qiu et al., 2012; Qi et al., 2020). In a different study (Jradi & Riffat, 2014; Kaushik & Sekhar, 2023), a heat and block exchanger was used to integrate a dehumidifier and evaporative cooler in a combined system that included the generator and KCOOH solution as a desiccant.

The average COP of air-functional was 0.72, and the achievable dehumidification rate ranged from 0.15 to 0.4 g/s for inlet air temperatures of 30 to 35°C and inlet air relative humidity of 51 to 70%. (Kaushal & Sharma, 2020). In an experiment, Conde (2004) examined the cooling capabilities of a liquid drier based on LiBr, LiCl, and KCOOH solutions. While the KCOOH solutions had a greater rate during the regeneration phase, the LiCl and LiBr solutions had higher rates of dehumidification. The flue gas waste heat from the biomass boiler was used to power an experimental study in the liquid dryer cooling system (Watanabe et al., 2019; Ren et al., 2019).

The average drop in relative air humidity was between 12.9 and 13.3% at a KCOOH concentration level of 0.47 and an airflow rate of 24,000 L/min. Ionic liquids (ILs) are molten salt at room temperature and are typically characterized by organic cations and inorganic anions (Shukla & Modi, 2023; Naik et al., 2020). It can take the place of other fluid desiccants since it is non-corrosive, non-flammable, and has good thermal and chemical stability (Dai et al., 2001; Ghazi et al., 2023). However, the experimental analysis of the system performance of ionic liquids integrated with LDCS, namely [BMIM-BF4] and [Dmim-Oac], has not received much attention (Kawamoto et al., 2016).

As a result, the study found that [Dmim]OAc could attain the moisture removal efficiency at an inlet mass concentration of 81.7% that was achieved with LiBr at an inlet mass concentration of 45.0% and LiCl at an inlet mass concentration of 40.9%. After a year of field testing in an LDCS, [P4441] [DMPO4] demonstrated consistent system performance of 80% electricity savings and 20% cost reduction compared to the typical LiCl desiccant system LCDS employing 30% mass concentration of LiCl (Shaharier et al., 2024).

Mathematical Model and Numerical Evaluation

Figure 11 shows the flow passage of liquid dehumidifier and regenerator air channels created by stacking two kinds of paper having wave angles alternatively. These sheet structures may be regarded as walls where the gaps are constant. (Figure 11) displays the coordinates and the physical model setting as shown below. The line y1 indicates a direction across to the flow of the incident film which begins at '$\mathbf{0}_1$' on the wall of the liquid-solid boundary. The y2 axis is a cross-flow direction and has taken its origin '$\mathbf{0}_2$' from the interface of the gas and liquid phases. The arrow above indicates the direction of airflow, which is being blown by the fan while the other arrow denoted from which Z-axis demonstrates the positions of the falling film along the X-axis while subject to gravity. D is the air channel spacing as utilized, and d is the thickness of the descending film.

The following key presumptions are established to build a mathematical model that accounts for the heat and mass transport during the regeneration phase and the dehumidification process (Wang et al., 2023):

1. It is expected that water vapor will not dissolve in process air;
2. The humidity of humidified air is equal to the humidity of the liquid desiccant solution, and the air temperature is the same as the temperature of the desiccant film that falls at the liquid-gas phase interface.
3. The laminar falling film and there is no effect of wave-like action at the interface.
4. Specifically, the falling film thickness is not variable;
5. Some limitations that imply a lack of (1) slight film sliding effect between the falling film and the process air; (2) lack of any provision to recognize buoyancy force.

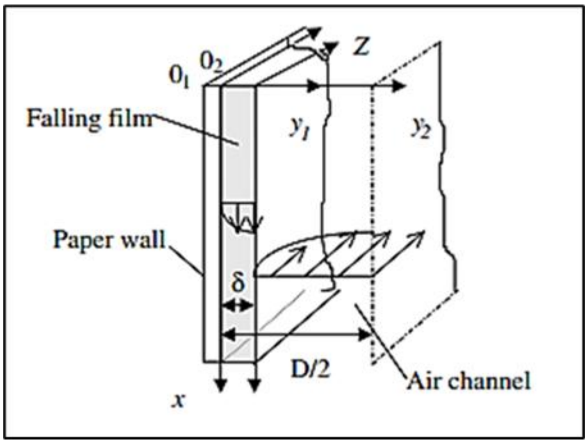

Figure 11. The coordinate system (Wang et al., 2023).

Basic Falling Film Equations

When the liquid film development rate is regular and slow under certain conditions. The average velocity of a falling film under gravity, particularly in laminar flow is defined as (Chuanshuai et al., 2019).

$$u_w = \frac{\rho_w g \delta_w^2}{3\mu_w} \tag{1}$$

The falling film thickness can be estimated as follows:

$$\delta_w = \left[\frac{3\Gamma\mu_w}{g\rho_w^2}\right]^{1/3} \tag{2}$$

The following are the mass conservation and energy balance equations for the falling film:

$$u\frac{\partial T_S}{\partial x} = \alpha_s \frac{\partial^2 T_S}{\partial y_l^2} \tag{3}$$

$$u\frac{\partial C_W}{\partial x} = D_s \frac{\partial^2 C_W}{\partial y_l^2} \tag{4}$$

Moist Air Basic Equations

In the case of a dehumidifier with a liquid desiccant in addition to in the regenerator working chamber, the direction of the falling film circulation is also perpendicular to the airflow. The equations that describe the air in the process can be derived below subject to the following assumption. The conservation of momentum in the z and y2 directions respectively are written as follows:

$$w\frac{\partial w}{\partial z} + v\frac{\partial W}{\partial y_2} = \gamma_a \frac{\partial^2 w}{\partial y_2^2} - \frac{1}{\rho_a}\frac{\partial P}{\partial Z} \tag{5}$$

$$w\frac{\partial v}{\partial z} + v\frac{\partial v}{\partial y_2} = \gamma_a \frac{\partial^2 v}{\partial y_2^2} \tag{6}$$

The following is the expression for the continuity equation:

$$\frac{\partial w}{\partial z} + \frac{\partial v}{\partial y_2} = 0 \tag{7}$$

Below is shown the conservation of energy in the air process:

$$w\frac{\partial T_a}{\partial z} + v\frac{\partial T_a}{\partial y_2} = \alpha_a \frac{\partial^2 T_a}{\partial y_2^2} \tag{8}$$

Likewise, the conservation of humidity in the air process is written as:

$$w\frac{\partial C_v}{\partial z}+v\frac{\partial C_v}{\partial y_2}=D_a\frac{\partial^2 C_v}{\partial y_2^2} \qquad (9)$$

Conditions for Matching Boundaries and Interfaces

To solve the aforementioned equations, boundary conditions must be met. The following is a list of them:

$$x=0;\ T_S=T_{S0};\ C_s=C_{s0};\quad z=0;\quad T_a=T_{a0};$$
$$\omega=\omega_0;\ y_1=0;\ u=0 \qquad (10)$$

The authors believe that the diffusive concentration gradient of the liquid desiccant film will be negligible close to the solid-liquid wall interface, whereas the velocity gradient of the falling film will also be comparatively trivial closer to the liquid film interface. In the case of air to be used in the process, the flow rate of air is zero at the gas-liquid interface. Additionally, the liquid and gas side solutions need to satisfy the following requirements for interface compatibility:

1. Temperature continuity is expressed as follows

$$T_s|_{y_{1=\delta}}=T_a|_{y_{2=0}} \qquad (11)$$

2. Equation (12) expresses the equilibrium state of water vapor at the liquid-gas interface, assuming that the vapor pressure of the liquid desiccant at the prescribed concentration and temperature is equal to the water vapor pressure of humid air at the liquid-gas interface:

$$P_{Vf}=P_{va}\qquad Where\quad P_{vf}=F(T_{sf},C_{sf}) \qquad (12)$$

3. The mass balance is written as follows:

$$-\rho_s D_s\frac{\partial C_W}{\partial y_1}\bigg|_{y_{1=\delta}}=\rho_a D_a\frac{\partial C_W}{\partial y_2}\bigg|_{y_{2=0}}+\rho_s u_s\frac{\partial C_w}{\partial x}dy_1 \qquad (13)$$

4. The interface's energy balance indicates:

$$-\rho_s u_s C_{ps}\,.\,dy_1\frac{\partial T_S}{\partial x}+\lambda_s\frac{\partial T_S}{\partial y_1}\bigg|_{y_{1=\delta}}=\lambda_a\frac{\partial T_a}{\partial y_2}\bigg|_{y_{2=0}}+\rho_a D_a\frac{\partial C_v}{\partial y_2}\bigg|_{y_{2=0}}q_i \qquad (14)$$

On the other hand, q_i, or the heat of mixing, is emitted during the dehumidification process and needs to be absorbed to replenish the liquid desiccant. Where: u= velocity, ρ= density, μ= viscocity, δ= thicness, g= gravity, Γ is the total flow rate, T, α, c, and Ds are temperature, thermal diffusivity, absorbate concentration, and mass diffusivity, respectively. , δ, η, and u¯ are boundary layer thickness, non-dimensional "y", and average velocity, respectively.

Two such heat forms involved in the transfer process at the liquid gas interface are the sensible heat transfer as well as the latent heat transfer. Regarding the control of temperature, heat exchange operates based on a temperature gradient near the liquid/gas interface, especially in the liquid phase of the substance that has undergone evaporation, while mass transfer energy control is accomplished by the gradient in the humidity of the liquid-gas interface.

Numerical Simulation

The viability of the liquid desiccant dehumidification generation system under the aforementioned parameters, as well as the mass and heat transfer processes, was investigated based on the model described above. A calculation program using the mathematical model has, however been developed. The following is the program's computation process:

There is known information in some inputs, including air mass flow rates, liquid desiccant solution, structural characteristics, air humidity, and inlet temperature.

1) Utilizing this information, the site calculates the thickness and velocity of fixed laminar falling film using the laminar film thickness formula and velocity.

2) Since a variety of factors influence the honeycomb wall channel's design parameters, the following should be included in the design requirements:

3) If the air flow is turbulent, calculate the airflow field in the honeycomb wall channel using the mixing length model.

4) Calculate the temperatures of the liquid falling film and air in air channel, and forecast the temperature behavior of the falling film inside the interface.

5) The subprogram for the liquid desiccant's thermal and physical properties is set up to determine the interface concentration of the falling desiccant film, the concentration distribution in the falling liquid film and the moisture distribution of the humid air in the air channel.

6) Verify the liquid-gas interface's mass balance. When this is done, item no. Proceed to the following step if this condition is true; if not, return to steps 5 and 6, iterating through steps 5 and 6 until accuracy is attained.

7) Need to control the energy at the liquid and gas phase boundary. If, however, a given condition is fulfilled one makes a transition to the following step, in case the condition is unfulfilled one returns to the previous step which is step 4 and continues with steps 4-7 until the search for accuracy is achieved.

8) Determine other performance parameters of this system and parameters characterizing the heat and mass transfer process and display the results.

Figure 12 represents a roadmap of calculations and results.

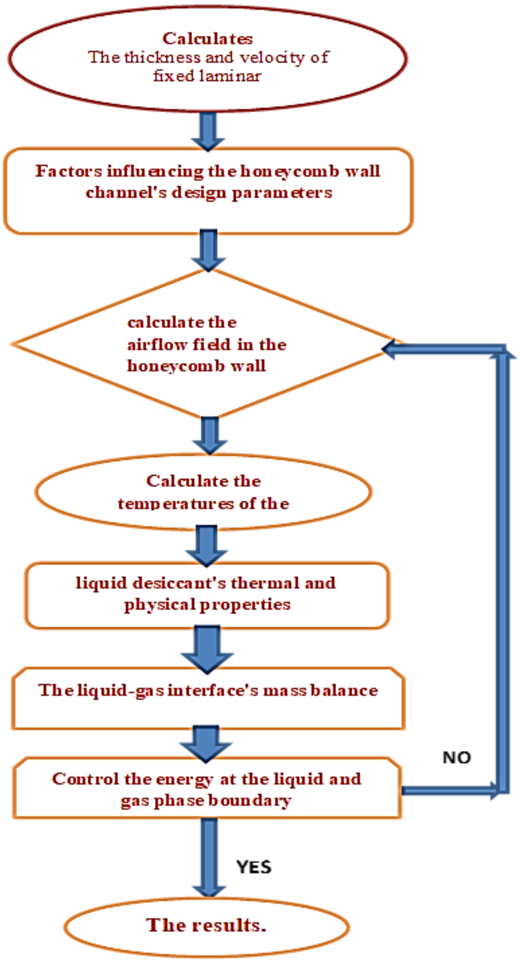

Figure 12. Calculations and results

It was followed by use of the software in system performance evaluation and system optimization of liquid-vapor compression desiccant hybrid air conditioning system at Northwestern Polytechnic University in Xi'an, China. For the case in which the flow is turbulent, the mixing length model of Chuanshuai et al. (2019) is applied to solve the governing equations specifically. Based on a honeycomb paper packed liquid dehumidification system, Wang et al. (2023) measured the heat and mass transfer processes in a dehumidifier and most of the heat generated in dehumidification is not for indirectly heating the process air as was mentioned in a previous section. In addition, it warms the desiccant solution. Here, a mathematical model is presented and validated to predict the mass and heat transfer procedures involved in the gas-liquid interface. Therefore, the Nusselt number of the liquid side of the sphere approximates to 2.84 in the case of the gas side, 6.54 and in the case of the Sherwood numbers, it is 5.40.

Conclusion and Future Trends

In the area of energy saving and environmental safety, an enormous number of research activities have been undertaken. Much of this work is aimed at looking for a solution to the inefficient Evaporative air conditioning systems that are energy-intensive and use environmentally nasty fluids. In this direction, several researchers have focused on Liquid cooling and drying systems thanks to their energy-saving and environmentally friendly technology.

1. The dehumidification and cooling processes of liquid dryer systems are improved by internal cooling. It causes the systems to deliver fewer pressure drops and require lower solution flow rates. The systems become small and integrate with internal cooling. The mean concentration of a solution is the major factor in the internally cooled GLC and the temperature of the solution controls the process in adiabatic GLC.
2. Dehumidification results from both condensation and the absorption of liquid desiccant when the cooling water used for indoor cooling is below the air's dew point. From the analysis of the above-indicated phenomena, it is observed that the mass transfer coefficients of the former are equal, respectively, and the same as the mass transfer coefficients of the latter.
3. As airflow rates and humidity ratios steps were raised, absorption rates were raised and dehumidification efficacies were lowered. On the other hand, raising the flow rate and concentration of the inlet desiccant enhanced the absorption and dehumidification rates.
4. Humidity and the inlet air temperatures have a positive effect on the performance of panel systems and are therefore ideal for hot and humid regions. It is possible to cool and dehumidify at the same time making the plate systems compact.

Hence, the mix of liquid desiccant dehumidification with evaporative cooling is the most successful of all the experimental systems and deserves much attention. Combining the best liquid desiccant with the best liquid desiccant gives a greater advantage, and if combined with the worst, it improves the worst, leading to increased efficiency and reduced cost. Furthermore, the various types of liquid desiccant and their blends as employed in research applications are used in different proportions and their behavior concerning internal cooling may also be different. This is where insight into which liquids can gain the most from internal cooling is considered valuable.

Recommendations

1. Further studies are needed on the long-term stability and performance of Ionic Liquids in practical systems."
2. Development of more accurate mathematical models that account for the variation in the desiccant solution film thickness."
3. Conducting standardized experimental comparisons between different desiccant types (e.g., LiCl, CaCl2, KCOOH) under identical operating conditions."

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest

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