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Liquid Desiccants Applications in Cooling and Dehumidification – An Overview

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Abstract

Potential option to replace the traditionally used vapor compression system with desiccant based dehumidification and cooling to overcome the problems in VCR use like as substantial consumption of high grade electrical energy and to eliminate the use of the CFC based refrigerants which are responsible for the depletion of ozone layer. The desiccant cooling can be proved to be an efficient in highly moist atmosphere to handles the latent cooling load of the conditioned space. The present overview explains about the detailed ideas for making use of various chemicals as the desiccant solution for their optimum cost and characteristics. The desiccant cooling can handle both humidity and temperature separately and effectively to produce necessary thermal comfort within the conditioned space. The desiccant cooling can find optimum use of renewable solar energy in air conditioning by applying them for desiccant regeneration to lower the consumption of electricity which produced mostly by fossil fuel based power plants which leads to problem of pollution subsequently. The present review provides the direction for effective use of the desiccant based cooling for separable control over temperature and humidity in case of both residential and industrial use to ameliorate the dual - energy and cost saving.

Keywords: Air-Conditioning; Desiccant Dehumidification; Liquid Desiccant; Reactivation Temperature

Introduction

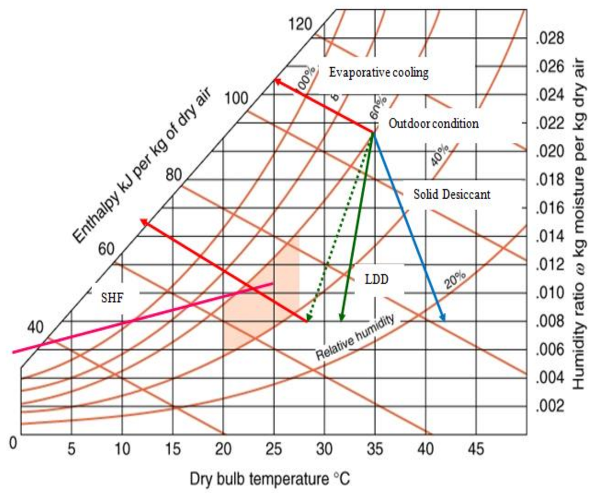
In this era of modernization, the huge expenditure is made now a days on energy required for producing the necessary cooling to maintain the thermal comfort as it is being switched from luxury to a necessity considering harsh ambient. Furthermore, the developing regions of the world, particularly countries like India, Pakistan and Srilanka etc. have grown their awareness of benefits of human comfort in various building cooling applications. These are countries where air conditioning industry has risen to a state of the exponential rate of growth past few decades. The traditionally used VCR systems that substantially consume the high grade electrical power as running the compressor used in the

VCR system. As a result, the substantial amount of electricity is used for cooling the conditioned space. Due to above mentioned reasons why distribution systems for electricity can be overloaded as excess electricity demand by the air conditioning. So, it now high time to modify the design of building such the air conditioning can be maintained with down sized active cooling system. Another aim is to develop air conditioners that run on freely available intensive solar radiations during the hot summer season.

But these changes are not enough. Now the air conditioning industry must look at the way that cooling is done and should adopt changes that will make it cost comparative and eco-friendly. The conventional air conditioning processes typically makes use of a direct expansion evaporator especially to control the humidity of room air. A very low temperature sensible cooling coil can handle both 75% of its total cooling demand as effective temperature control over room air and 25% as moist air load to control the humidity of room air. Hence, it is a cumbersome way to dehumidify air as it consumes lot of energy to separate water vapor from conditioning air in above conventional way. In many applications requires dense human occupancy, this latent/sensible split must be reversed if indoor humidity should be effectively controlled to maintain necessary air conditioning within the conditioning room.

We know that evaporative cooling is the oldest means of cooling the outdoor air, but this cannot maintain the required air quality in at places where large human gathering is covered like as school, hospital, bank, theater etc. generates large moist air. For effective thermal control of indoor air of closed rooms are often uncomfortable and unhealthy to the occupants because the drastic reduction in oxygen level. A typical summer outdoor condition for a moist condition of typical tropical condition is shown in (Figure 1) It is graphically shown that an efficient evaporative cooling can cool the air to 27°C, but the relative humidity will be around 100%, which will lead to perspiration to the occupant within the test room. Evaporative cooling can effectively maintain the thermal comfort within the test room if the air can be dehumidified efficiently first before being temperature controlled. This can be obtained by the use of the desiccants materials. Desiccant systems are commonly classified such as the solid desiccants or as liquid desiccant.

Figure (1): The cooling process on psychrometric chart for a moist climate of typical tropical region.



Solid-desiccant cooling systems mainly consist of a moisture laden desiccant wheel having number of passages known as matrix channel. Namely the process air section and reactivation section. The very low speed about 12 RPH of desiccant wheel permits continuous adsorption of the process air. As there is no provision for the active cooling within the desiccant wheel and the dehumidifier itself conveys some heat energy from the regeneration air to the process air, the hot and dehumidified process air leaves the dehumidifier at a higher enthalpy than its temperature at the inlet to the wheel through process air section. The process is known as dehumidification of the process most air which is supplied at the dehumidifier entry as shown by the blue colour line in (Figure 1).

Both solid and liquid desiccants are being used in dehumidification applications, but liquid desiccant absorbers are becoming more attractive because of the possibility of simultaneous cooling during the process of dehumidification. Liquid desiccants also have the capability to absorb inorganic and organic air contaminants and microorganisms [1,2]. Most of the systems already developed make use of solid desiccants, with relatively high regeneration temperatures. One alternative is the use of liquid-desiccant systems. In these systems, lower regeneration temperatures can be employed, allowing for a more efficient use of heat from low temperature sources, for example, flat plate solar collectors [3]. In the air conditioning systems, the use of liquid desiccant systems has become more popular in the past decades due to the need for reduction in the consumption of energy [4,5]. The capability of these systems in handling latent heat in the space that will be conditioned by a dehumidifying process also allows control of the humidity without the overcool/reheat scheme as done in a regular ventilating and air conditioning system [6]. The vapor pressure difference between the air and the desiccant is the moisture transfer driving force, which makes desiccant to absorb the moisture or deliver the moisture to the air. In the liquid desiccant air conditioning system, air is dehumidified by directly contacting the concentrated desiccant solution in the dehumidifier and the diluted desiccant solution from the dehumidifier will come to the regenerator in which it is re-concentrated. Low grade heat can be utilized to regenerate the desiccants [7-10] such as solar energy and waste heat (Figure 2) shows the line sketch of typical liquid-desiccant assisted cooling systems. The absorber and regenerator column both are provided with the desiccant bed to flow the liquid desiccant material. The desiccant initial lowers its temperature by circulating over the desiccant stationery bed of the cooler.

The humid room air working as the process air coming from test space directly flows through this desiccant laden bed and it cools and adsorbs the moist air while makes use of this liquid desiccant. A negligible amount of leakage of stream of desiccant always occurs while it passing from absorber to regenerator column where the desiccant solution is re-concentrated using reactivating thermal energy. Again, the desiccant flows above desiccant bed laden contact media during the next cycle. However, the desiccant is now first risen its temperature, typically to between 48°C and 84°C which is comparatively lower temperature, prior to it passing on the desiccant laden bed. At the same time this creates the great opportunity makes the use of freely available solar thermal energy for air conditioning to control temperature and moist room air. Air flow occurs over the bed, desorbs the water vapor absorbed by the desiccant solution, and exhausted to atmosphere. The flowing rate of desiccant solution in both cooler and regenerator has been found lower for basically the two reasons:

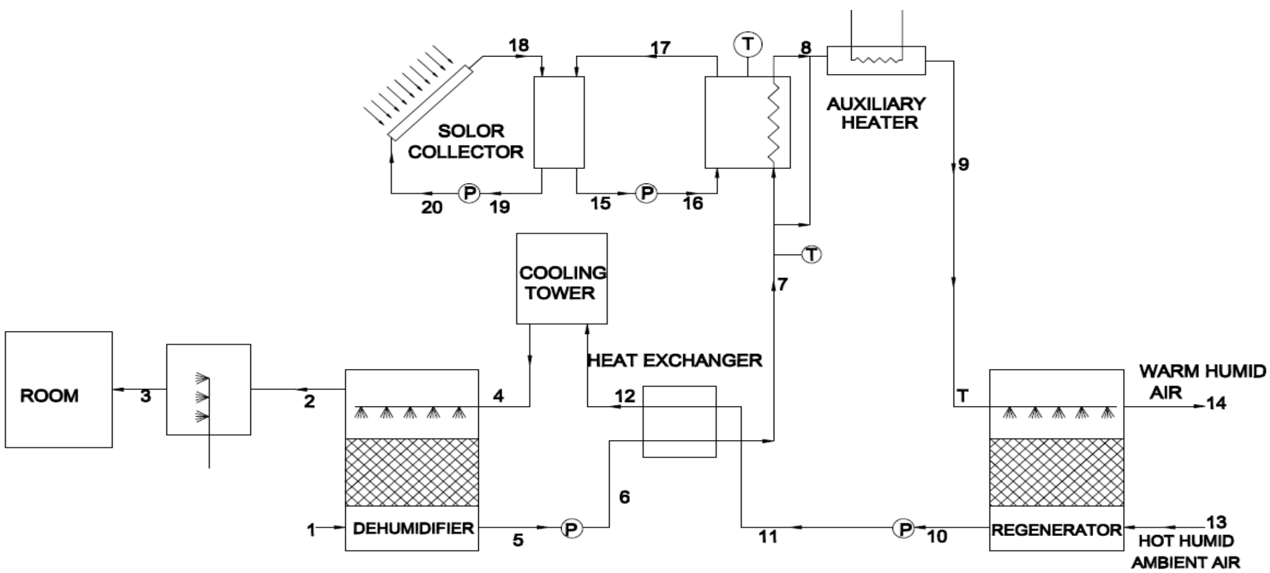
(1) The entire internal area of the contact of desiccant solution over the desiccant bed should be wet with the desiccant enriched solution.

(2) The flow rate of the desiccant solution make in such a way that it should have enough thermal capacity which does not change the

heat of desiccant absorbed.

At large flow rates, small molecules of desiccant while flowing over the bed. These small molecules of the desiccant materials are attracted greatly by the moist air before flowing through the conditioner to enter the room as conditioned air. So, a conventional liquid-desiccant system must use a eliminator to separate out desiccant molecule from the regenerator to the conditioned space where it might get in touch with occupants and to effect their health. In well-maintained systems, the droplet filter/demister gets perfectly removed the desiccant fume. The process is shown by the typical dehumidification cycle over a psychrometric diagram. The large removal of moist air can further be ameliorated if the liquid desiccants can be cooled in the dehumidification process. The dashed line in psychrometric chart represents the dehumidification process of moist room air circulates within the room. After dehumidification a simple evaporative sensible cooling can be provided to obtain designed air conditioning.

Figure (2): Schematic layout of liquid desiccant assisted cooling system



The main merit in use of the liquid desiccant assisted dehumidification and cooling is its ability to supply biologically uncontaminated air on removing the air borne contaminants due to diluted indoor environment. The solutions used would separates out any bacteria available in room air on contact with the desiccant solution. Additionally, there are no wet surfaces as absence of any condensation, such as those found on VCR cooling coils that promotes bacterial growth is absent here. This makes typical application of liquid desiccants ideal for use in hospital facilities and in intensive care such as pharmaceuticals. The latest developments and future work required for commercialization and popularity of LDCS (liquid desiccant cooling systems) are briefly demonstrated in the following sections.

Previous investigations on liquid desiccant assisted cooling

Previously there have been number of

research innovations were made by investigators for capturing the benefits of combining the use of desiccant dehumidification in a renewable solar energy in air conditioner. The past work carried out by the different investigators on liquid desiccant cooling and dehumidification systems can be categorized as selection of desiccants and development of effective dehumidifier.

Selection of desiccants

The choice about type of desiccant will have a great impact over the choice of layout of the LDCS. Glycols other materials which are traditionally used in different commercial applications, they have their own merits and limitations. Some examples given as the lithium chloride and lithium bromide are most powerful adsorptive equipment: a saturated solution of lithium bromide separates the moisture at a great amount from the outdoor air to 9 % RH at the same time the lithium chloride to 12 %. Unfortunately, operating cost among the lithium salts are not affordable to common applications; about \$6.69 and \$9.68 per kilogram, respectively. A 23 ton liquid-desiccant system actively provided with 91 kg of salt [11]. Moreover, halide salts are responsible for corrosion in different air conditioning applications.

Glycols are the inferior types of desiccants commonly used different residential and commercial cooling applications. Both tri-ethylene and propylene glycol are highly toxic, and their suitability with most of the material improvised the investigators to apply them in LDCSs that are designed for various commercial cooling equipment's [12,13]. However, all glycols have one undesirable chemical property that they are easily evaporate in the ambient air. A mixture of 97% tri-ethylene glycol (TEG) and 5% water will dehumidify the moist process air to the equal dew point as a 48% lithium chloride solution. However, at equilibrium, the molar concentration of the glycol in the air is found as 1.2 % that of the water vapour presented in air moisture. In an air cooling where a 12,000 m^3/h LDCS operates for 2500 hours per year, the annual loss of TEG in the cooler would be higher than 4700 kg. [13] carried out performance tests on various combinations of lithium chloride and calcium chloride concentrations as a reasonable-cost substitute to conventionally working lithium chloride.

The operational expenditure of using the calcium chloride is slightly about one fourteenth that of the lithium salt concentrations. A through experimental study of the LDCS and its effectiveness in cooling would be needed to evaluate whether the LDCS operating with the 50/50 mixture is an attractive alternative to the VCR based cooling system. Among the commonly used concentrations that might be commonly used as absorbents, lithium chloride has by far been the commonly finds a application in commercial cooling. Their priority can be violated even if the use of lithium bromide can work efficiently at all possible concentrations at which it is a very powerful absorber for dehumidifying the air. Indeed, lithium bromide is established absorber which applied water as a refrigerant in the cooling system. An LDCS that used a widely used common desiccant material than lithium chloride might have one prime benefit: it might lead to a commercially cooled LDCS that does not require demand of the ordinary cooling water.

An LDCS with dry air cooling of the conditioner would not need a cooling tower or other source of evaporative based cooling system. In addition to being a simpler system to install and maintain, it does not require useful water resources. As the LDCS neglect use of water for cooling, but by switching air conditioning loads from high grade electricity to primary form of energy such as solar heat which is available freely or at low cost as industrial waste heat, then water demand at the power plant would be drastically reduced [14,15].

Development of efficient dehumidifier

The packed-bed conditioner typically used in different innovative research on LDCSs. The foremost work regarding the packed bed absorbers can be studied earliest [7]. The investigations carried out on packed-bed desiccant regenerators recently includes the performance test based on experimental and simulation study made [16] conducted experimental tests on application of various types of the packed-bed absorbers operated along the lithium chloride measured for different climatic zones. Initially the investigators were studied absorbers as internally cooled units that make the application of various copper tubes or polypropylene tubes as the higher surface contact between the desiccant solution and air.

Among all of them copper tubes rusted earlier by the use of liquid desiccant in the dehumidifier, and the polypropylene tubes were found very cumbersome to wet resulted to poor heat transfer. Adiabatic packed beds having its volumetric surface area around 288 m^2 per m^3 are commonly applied. A 18 kW LDCS was performed tests for the estimation of its effectiveness [17]. With use of thermal energy for regeneration is mostly provided by freely available low grade solar thermal energy, the LDCS had the COP evaluated as 0.86. [15] numerically simulated packed-bed, lithium chloride absorbers that used a random, polypropylene packing having the exposed surface area of 212 m^2 per m^3.

The results show that the lithium chloride solution is not found common commercial application as it has poor surface contact with the surrounding area is resulted to poor heat transfer. Accepted estimation [18] among the measured and modeled performance was derived after a standard relation was accepted to estimate the fraction of wetted surface area in the desiccant bed. [19] conducted experimental tests on desiccant absorber that used structured packing flooded having commonly applied a solution of lithium bromide by simulation tests. Performance is predicted for the cooler and its different dehumidification effectiveness at various flow rates of the process and regeneration stream, desiccant inlet temperature, desiccant inlet concentration, air temperature, and air humidity ratio [20,21] developed numerical scheme for the absorption rate prediction within liquid-desiccant packed-bed systems which primarily included minimal change in desiccant concentration through the packed bed and a Lewis number of one. The investigators found that their analytical solutions match acceptable with its numerical solutions and with experimental data from other earlier research reported in literature. [22] Conducted various measuring tests experimentally on a LDCS that uses cross-flow desiccant absorbers. During performance test, each of different set-ups processed approximately 2400 m^3/h of fresh outdoor ventilation air using various packed beds arranged such that mass flows are carried equally through all sections. Each of the section beds was passing the lithium bromide between 43% and 47% by weight. The desiccant was flows across the packed bed desiccant absorber surface. Packed-bed sensible evaporative coolers supplied the coolant to lower the temperature of the desiccant in succeeding heat exchangers. The moist room air degrades the performance for the sensibly cooled evaporative coolers in humid climate. The moisture substantially eliminated from the desiccant in a packed-bed regenerator whose regeneration heat supplied by passing the warm water having temperature between range of 75°C and 78°C. [22] found that the absorber COP was 0.83 and the COP for the overall system is evaluated as 1.54.

The rate of desiccant solution flow in packed-bed cooler found to be very large, both to ensure perfect surface contact between the packing and to eliminate heating of the desiccant solution. Although, the first objective-complete wetting-might be realized at comparatively small volume by slight addition of the surfactants to the desiccant or for better the surface contact of the packing to increase its surface energy, the second-keep the desiccant cooling always require a tremendously high flooding rate. Many other researchers also conducted numerical study on internally cooled conditioners. [23] established numerical scheme for the evaporative cooled cross-flow conditioner that they performed measuring tests in laboratory [24]. Their model carried out energy and mass balances on incremental control volumes using standard correlations for various laminar flows. The Nusselt theory for laminar flow is estimated to estimate the layer of the liquid films. The model predicted the effectiveness of the cooler reasonably well with most data falling within error band range 13% of the model's estimations [25] developed numerical scheme to estimate effectiveness of cooler in which the air and desiccant flows are counter-current and the flows are assumed as to be laminar. Three different types of models were designed for test measurement. The absorption of moisture from humid room air is predicted based on standard correlations between desiccant and moist air.

Moreover, the heat transfer and mass exchanges process among them can also be modeled to determine desiccant film thickness for the solution. The ratio between a desiccant and air can be taken as 0.12 to predict the dehumidifier effectiveness within range of 9 % accuracy. Experimental performance on adsorber in previous investigations and earlier researches has been tabulated in (Table 1).

Table (1): Performance test results on dehumidifier in previous investigations and researches[26].

Author	Desiccant				Air					L/G Ratio	ε_y	Remark
	Type	Temp (°C)	Conc (%)	Flow rate/Flux (l/min)	Flow rate/Flux (l/min)	Temp (°C)	Humidity	ΔT (°C)	ΔW (g/kg)			
Ani et.al. [27]	LiCr	25-27	35-40	3.76-5.01	4.9-6.4	-	-	-	-	-	-	SP,CF, COP_{hyb} =2.6-4.9
Longo and Gasparella [28]	LiCr	-	40	-	40-96	30	18.9	-4	-7.2	-	-	SP,CF,COP_{hyb} =2.7-3.0
Elsarrag [13]	TEG	29;35	92	1.7-2.2	0.94-2a	-	17-26	-	-5.5 to -11	1.9-2.3	0.45-0.85	SP,CF, ΔP= 35-140 Pa/m

Hassan and Hassan [29]	LiCr	30.1 30 30.5 30.1	34.6 34.3 43.4 33.9	6.124a 6.113a 6.287a 6.273a	0.89a 1.513a 1.183a 1.214a	30.1 30.2 40.1 30.3	18 18.1 18 14.2	1.2 2 -7 0.8	-7.6 -7.3 -6.5 -3.9	6.88 4.04 5.31 5.17	0.75-0.84	RP,CF,210m²/m² Des. ΔConc=0.1% Des. ΔT = 1.4-2.7
Patek and Klomfar [30]	Mixture	-	-	-	77.9-113.3 77.9-113.3	35 35	22.3 14.1	-18.3 -17.2	-13.7 -7.2	-	-	COP_{hyb} = 2.4 ΔP = 100 Pa
Saman et.al [31]	LiBr	-	-	-	-	-	-	-2 to -11	-2 to -8	-	-	Cooled FF,ST,PF
Jain et.al [32]	TEG	22.9 23 20.5 20.2 21.8	96.8 92.4 95.2 92.5 92.2	0.057b 0.063b 0.058b 0.057b 0.052b	0.07b 0.07b 0.07b 0.07b 0.051b	20.6 31 19.4 28.6 21	12.48 16.88 8.17 16.93 8.95	2.5 -8.3 2.1 -4 1.2	-8.1 -11.23 -4.54 -12.46 -4.21	0.81 0.90 0.83 0.81 1.02	.96 1.06 1.01 0.94 0.88	Cooled FF,ST,CF ΔP =1736 Pa, Drift=5.6-9 g/min
Ahmed et al. [33]	LiCl	-	-	-	-	-	-	-	Up to -20	-	-	-
Lazzarin et.al [34]	LiBr	16.1-34.1	53-57	0.018-0.13b	3.67	23.6-35.4	1.4-18.7	-	-3 to -11	0.35-1.9-	0.25-0.88	RP,CF
Liu et.al. [35]	LiBr	20.1-29.5	42.6-54.8	0.3-0.64b	0.31-0.47a	24.7-33.9	10-21	-	-	-	0.4-0.7	SP,Cross flow
Yutong and Hongxing [36]	LiCl LiBr KCOOH	23.4-24 23.7 21.9-24.8	39.2-40.6 51.9-53.9 72.8-74.0	0.10-1.17a 0.16-1.39a 0.09-1.23a	0.43-0.47a 0.44-0.47a 0.48-0.52a	24.3-37.6 23.6-36.7 22.6-35.8	7.3-23.3 8.2-22.8 8.8-20.7	-	-2 to -17 -3 to -18 -2 to -13.5	0.23-2.6 0.35-3.0 0.2-2.5	0.3-0.9 0.3-0.9 0.3-0.9	RP,CF ΔP=25-45 Pa/m Negligible sensitivity of ε_y and ΔP to desiccant
Mago-Goswami [37]	LiCl	27-30	35	0.35-0.51b	0.6-0.7b	26-29	11.6-13.9	-	-2 to -4	-	-	RP,CF
Oberg and Goswami [38]	TEG	24-36	94-96	4.5-6.5a	0.5-0.15a	24-36	11-23	-	-8.5 to -10	4.5-11	0.8-0.9	RP,CF, ΔP=30-210pa/m

Patil [39]	PG	-	-	-	-	4.4	3.12	-2.77	-1.4	-	-	Cooled spray Tower,
Pietruschka et al. [40]	LiCl and $CaCl_2$	27 27	43 43	1.67 1.67	3.3 3.3	26 26	11.6 11.6	5 1	-4.2 -5.7	- 0.13- 0.28	- 0.2- 0.9	, SP, Cross Flow,Cross PHE,cooled
Saman and Alizadeh [24]	$CaCl_2$	-	40	0.06	0.16-0.47b	23 33	7.4	-	-3	-	0.3-0.9	PHE,cross flow,cooled m_w = 0.08 Kg/s
Abdul-Wahab et.al. [41]	TEG	28-45 31	93-98 95.6	0.13-10a 0.23	1.5-2.613a 2.07	25.4-44 31	- -	-	-0.1 to 0.24c -0.15 to 0.2c	0.06-2.07 0.11	0.1-0.7 0.16-0.4	SP of wood,CF 77-200m²/m²
Zurigat et.al. [42]	TEG	28.2-45.5 31.5 31.4 31	28.2-45.5 31.5 31.4 31	0.13-0.82a 0.13a 0.82a 0.23a	1.5-2.07a 2.07a 2.07a 1.73a	25.4-44 29.9 29.9 30.6	16.2-20.7 20.6 16.9 21.8	-	- -4.6 -4.8 -3	0.1-0.4 0.06 0.40 0.13	0.19-0.45 0.31 0.43 0.19	SP of wood/Al, CF Wood SP Wood SP Al Sp
Y.Yongao et al. [43]	H_2O/ LiCl	25-30	38-40	104.2c	74.9	28.5-34.5	11.8-18.5	-	-	1.3912		Structured packed tower

AL-Aluminiun, RP-Random Packing, SP- Structured Packing, COP_{hyb} –hybrid COP, PHE-Plate Heat Exchanger,CF-Counter Flow, FF-Film Falling/Wetted Wall, ST-Shell and Tube, PF-Parallel flow, PG-Polypylene glocol, m_w –Water flow rate .

Measured in kg/m² s, [b] Measured in kg/m, [c] Measured in g/s

Table (2): Empirical formulation for dehumidification effectiveness [26]

Author	Correlation	Type of Tower/ Packing	Desiccant	Range of Validity
Abdu and Wahab Et.al [44]	$\varepsilon_y = 0.601 + 0.275L - 0.00072a - 0.0107TG\ in$	Structured Packing	TEG	77 < a < 200 0.15 < L (kg/m²/s)
Chung [45]	$\varepsilon_y = \left(1 - \frac{0.205\left(\frac{G_{in}}{L_{in}}\right)^{0.174} \exp\left(0.985\frac{T_{Gin}}{T_{Lin}}\right)}{(aZ)^{0.184}\,\Pi^{1.680}}\right) / \left(1 - \frac{0.152\exp\left(-0.686\frac{T_{Gin}}{T_{Lin}}\right)}{\Pi^{3.388}}\right)$	Random Packed tower	TEG and LiCl	Average error ± 7 %

Cheng et al. [44]	$\varepsilon_y = \left(1-\frac{0.204\left(\frac{G_{in}}{L_{in}}\right)^{0.6}\exp\left(1.057\frac{T_{Gin}}{T_{Lin}}\right)}{(aZ)^{-0.185}\Pi^{0.638}}\right)/\left(1-\frac{0.192\exp\left(0.615\frac{T_{Gin}}{T_{Lin}}\right)}{\Pi^{-21.498}}\right)$	Random Packed Tower	TEG and LiCl	Average error ± 10 %
Liu et.al [19]	$\varepsilon y = C_oG^{-0.2804}L^{0.3657}$ $\varepsilon_y = \left(1-\frac{0.642\left(\frac{G_{in}}{L_{in}}\right)^{0.1}\exp\left(-0.2\frac{T_{Gin}}{T_{Lin}}\right)}{X^{0.537}}\right)/\left(1-\frac{0.496\exp\left(-0.945\frac{T_{Gin}}{T_{Lin}}\right)}{X^{1.558}}\right)$	Cross Flow Dehumidifier	LiBr	$0.893 < L/G <. 273$ $0.42 < X < 0.49$ $< 24.7 < T_{a,in} < 33.9$
Martin and Goswami [44]	$\varepsilon_y =$ $1-48.345\left(\frac{L_{in}}{G_{in}}\right)^{\left(0.396\frac{\gamma L}{\gamma c}-1.573\right)}\left(\frac{h_{a,i}}{h_{L,i}}\right)^{-0.751}(aZ)^{\left(0.033\frac{\gamma L}{\gamma c}-0.096\right)}$	Random Packing Both Dehumidifier And Regenerator	TEG (90-95%) LiCl	$3.5 < L/G < 15.4$ $0.4 < h_{a,i}/h_{L,i} < 1.9$ $84 <_aZ < 262$ $0.8 < \gamma_L/\gamma_c < 3.2$

Nomenclature

ω = air humidity ratio (g/kg)

h= enthalpy (KJ/kg)

P = Partial pressure (kPa)

c = Salt concentration of desiccant solution(%)

Greek symbol

ε_{de} = efficiency of dehumidifier

ε_{re} = efficiency of regenerator

ε_h = Enthalpy Effectiveness

Subscript

in = inlet

out = outlet

a = process air

max = maximum

eq = equilibrium

g = gas

s= solution

L=Liquid

In above table the effectiveness of dehumidifier corresponding to the moist air condition of can also be estimated. Packed column using structure packing is widely preferred with packing densities of the order 250 m^2/m^3 to 470m^2/m^3, with height and diameter in the range of 0.42 – 0.67 m. The ratio of liquid to gas flow rate (L/G) ranges from 0.05 to 13. The efficiency of dehumidifier (ε_{de}) lies in the range of 0.11-0.92 except an example [32], where the value greater than 1. The reduction in the specific humidity of air is found about 17 g/kg. The hybrid COP is in the range 2.57 – 5.2. The variation in pressure is in the range of 12 Pa to 154 Pa. The different standard testing standard relations of dehumidification effectiveness of desiccant based dehumidifier are illustrated in (Table 2) The observations proposed by [45-47] were primarily proposed and evaluated packing, but it can be referred by many investigators afterwards for structured packing's [48]. Moreover, standard relations are used mainly in design for desiccant dehumidifiers only, correlation by [44,49] can be applied in case of packed bed type desiccant regenerator also.

The experimental error observed case in effectiveness evaluation was found as ± 0.08 for dehumidifier and ± 0.17 for regenerator. The relations proposed by [44,46,50] found to be more accurate as they are in non-dimensional form and account not only for the working existing room air and liquid conditions but also for the packing size. (Table 2) show empirical formulation for the dehumidification efficiency and regenerator performances respectively.

Research needs and innovations in liquid desiccant cooling technology

Important amelioration and advancements must still be made in liquid-desiccant technology if it is to be commonly applied for various cooling applications in commercial and house hold cased. These needs are as follows

The Identification of a non-corrosive desiccant to the regenerator

The halide salt solutions now commonly used in LDCSs are nontoxic, but found highly corrosive to contact metals. A liquid desiccant used for performance evaluation in desiccant cooling greatly for advances in technological innovations. The desiccant cooling can also be applied mainly in large scale for air conditioning of commercial and residential applications. The research for invention related to search for desiccant having large wettability can also be future direction [30,51-55].

The Development of a desiccant integrated air-cooled conditioner in HVAC application

Owners of smaller cooling systems tend to eliminate heavier and large cooling towers, which require comparatively higher repairing than they will accept. In some applications, the merits offered by the LDCS will overcome any possible reluctance to make use of a small cooling tower. However, market acceptance of LDCSs would be limited by the lack of modernization of an air-cooled unit. An air-cooled LDCS would have the merit of greatly lowering the comparatively great requirement for water created by conventional cooling, whether the demand is onsite or out campus [56-59].

High-efficiency regenerators in desiccant dehumidification

Simple, scavenging-air regenerators- the absorber which has wide spread application in LDCS are mostly limited to achieve COPs almost less than one. Many more modernizations should be carried out to rise the COP of regenerators. These advanced approaches basically consist of wide spread application of multiple-effect boilers and vapour-compression distillation. If this future advancement are to become a member of a high-efficiency LDCS in coming days, they must be innovated or advanced and demonstrated in commercial cooling applications [60-62]. Other high-efficiency separation processes should also be explored further to increase usability of desiccant cooling technology.

Enhanced heat and mass transfer phenomenon in dehumidifier

In mostly the internally cooled desiccant based absorbers were developed earlier by rigorous efforts carried out by constant efforts from [24,63] the process air travels among the contact surfaces at limited laminar Reynolds numbers. The these passages may be restricted mainly by vacant spaces in between, but the main work of these spacers is to keep the surface contact apart, not to spread water particles between the air and the desiccant solution surface. Surface enhancements such as fins, spines, and other extended surfaces are mostly used in heat exchangers to down size it further. Although the desiccant films that flow on the mating surfaces complicate the design of the regenerator and conditioner, approaches to ameliorating the heat exchange correlations might be analyzed further as a way to lower the size, pressure drop, and cost of these critical components.

Application of advanced evaporative cooling to LDCSs

The absorption capability of a LDCS that uses an internally cooled conditioner varies widely as the heat of the desiccant/air contact surfaces lowers. In similar other uses the conditioner gets exhaust the heat either directly or indirectly by the process of evaporative cooling. This reduces the temperature of the mating surfaces to a value above the WBT of the moist air that fastens the evaporative cooling. Advanced indirect evaporative coolers are basically designed to cool air below WBT of moist air that acts as the heat sink. The advanced evaporative coolers find a wide spread application in a LDCS has the great potential to expose to be a more commercially viable as well as competitive HVAC product in industrial market [64-66].

Active participation of desiccant quality and chemistry

Liquid absorbers commonly find wide spread uses in residential and industrial cooling units can get sometimes leads to chemical instability [67]. Chemical interactions among conventionally used desiccant and gaseous species in the moist air are more prone to occur. Once again, longer term operating experience with LDCSs is required to locate and summarize possible problems, and if problems are encountered, to rectify them to find the better results of the same [68].

Conclusion

Although now limited primarily to industrial HVAC applications, LDCSs could help solve the most pressing problems now facing the air conditioning industry:

- Peak electric energy based cooling requirement created by conventionally used VCR system.
- Indoor air quality gets affected sometimes for thermal cooling and excess humid indoor air level that can be difficult to cope up with conventional air conditioners.
- Pollution created by carbon emissions exhausted from the fissile fuel based power plants that used mostly by the use of electric based conventional VCR air conditioners.

In many desiccant cooling applications, the main requirement is that the desiccant must be chemically stable. Halide salts are conventionally used chemicals as a liquid desiccant that performs these potential criteria. The rusting of surrounding metals observed with use of halide salt solutions can be altered greatly by working with slightly lesser desiccant flow rates in absorbers column. At partially low flow rates, the desiccant solution can be cooled constantly over cooler and constantly heated in the regenerator to reduce variations in its temperature.

References

1. Chung TW, Ghosh TK, Hines AL, et al. (1995) Dehumidification of moist air with simultaneous removal of selected indoor pollutants by tri ethylene glycol solution in a packed-bed absorber. Separation Science and Technology; 30(7-9): 1807-1832.
2. Oberg V, Goswami DY (1998) A review of liquid desiccant cooling, advantages in solar energy. American Solar Energy Society; 12: 431-470.
3. Oberg V, Goswami DY (1998) A review of liquid desiccant cooling, in Advances in Solar Energy, K. Boer, Ed., American Solar Energy Society, Boulder, Colo, USA.
4. Feyka S, Vafai K (2007) An investigation of a falling film desiccant dehumidification/ regeneration cooling system. Heat Transfer Engineering; 28(2): 163-172.
5. Jain S, Bansal PK (2007) Performance analysis of liquid desiccant dehumidification systems. International Journal of Refrigeration; 30(5): 861-872.
6. Katejanekarn T, Kumar S (2008) Performance of a solar regenerated liquid desiccant ventilation pre-conditioning system. Energy Buildings; 40(7): 1252-1267.
7. Oberg V, Goswami DY (1998) Experimental study of the heat and mass transfer in a packed bed liquid desiccant air dehumidifier. Transactions of the ASME, Journal of Solar Energy Engineering; 120(4): 289-297.
8. Gandhidasan P, Ullah MR, Kettleborough CF (1987) Analysis of heat and mass transfer between a desiccant-air system in a packed tower. Transactions of the ASME, Journal of Solar Energy Engineering; 109(2): 89-93.
9. Lowenstein AI, Gabruk RS (1992) The effect of absorber design on the performance of a liquid desiccant air conditioner. ASHRAE Transactions; 98: 712-720.
10. Jain S, Dhar PL, Kaushik SC (2000) Experimental studies on the dehumidifier and regenerator of a liquid desiccant cooling system. Applied Thermal Engineering; 20(3): 253-267.
11. Lowenstein A (2008) Review of liquid desiccant technology for HVAC applications. HVAC&R Research; 14(6): 819-839.
12. Bansal P, Jain S, Moon C (2011) Performance comparison of an adiabatic and an internally cooled structured packed-bed dehumidifier. Applied Thermal Engineering; 31(1): 14-19.
13. Elsarrag E (2006) Dehumidification of air by chemical liquid desiccant in a packed column and its heat and mass transfer effectiveness. HVAC&R Research; 12(1): 3-16.
14. Ertas A, Anderson EE, Kiris I (1992) Properties of a new liquid desiccant solution-lithium chloride and calcium chloride mixtures. Solar Energy; 49(3): 205-212.
15. Fumo N, Goswami DY (2002) Study of an aqueous lithium chloride desiccant system: air dehumidification and desiccant regeneration. Solar Energy; 72(4): 351-361.
16. Gommed K, Grossman G, Ziegler F (2004) Experimental investigation of a LiCI-Water open absorption system for cooling and dehumidification. J. of Solar Energy Engineering; 126: 710-715.
17. Gommed K, Grossman G (2007) Experimental investigation of a liquid

desiccant system for solar cooling and dehumidification. Solar Energy; 81(1): 131-138.

18. Uemura T (1967) Studies on the lithium chloride-water absorption refrigeration machine, Technology Reports of Kansai University; 71-84.
19. Liu XH, Zhang Y, Qu KY, et al. (2006) Experimental study on mass transfer performances of cross flow dehumidifier using liquid desiccant. Energy Conversion and Management; 47(15-16): 2682-2692.
20. Liu XH, Jiang Y (2008) Coupled heat and mass transfer characteristic in packed bed dehumidifier/regenerator using liquid desiccant. Energy Conversion and Management; 49(6): 1357-1366.
21. Liu X, Jiang Y, Xia J, et al. (2007) Analytical solutions of coupled heat and mass transfer processes in liquid desiccant air dehumidifier/regenerator. Energy Conversion and Management; 48(2): 2221-2232.
22. Chen XY, Jiang Y, Li Z, et al. (2005) Field study on independent dehumidification air-conditioning system-I: performance of liquid desiccant dehumidification system. ASHRAE Transactions; 111: 271-276.
23. Saman WY, Alizadeh S (2001) Modeling and performance analysis of a cross-flow type plate heat exchanger for dehumidification/cooling. Solar Energy; 70(4): 361-372.
24. Saman WY, Alizadeh S (2002) An experimental study of a cross-flow type plate heat exchanger for dehumidification/cooling. Solar Energy; 73(1): 59-71.
25. Mesquita LCS, Harrison SJ, Thomey D (2006) Modelling of heat and mass transfer in parallel plate liquid-desiccant dehumidifiers. Solar Energy; 80(6): 1475-1482.
26. Khaamooshi M, Parham K, Atikol U (2013) Overview of ionic liquids used as working fluids in absorption cycles. Advances in Mechanical Engineering; 5: 1-7.
27. Ani FN, Badawi EM, Kannan, KS (2005) The effect of absorber packing height on the performance of a hybrid liquid desiccant system. Renew Energy; 30(15): 2247-2256.
28. Longo GA, Gasparella A (2005) Experimental and theoretical analysis of heat and mass transfer in a packed column dehumidifier/regenerator with liquid desiccant. Int J of Heat Mass Transf; 48(25-26): 5240-5254.
29. Hassan AAM, Hassan S (2008) Dehumidification of air with newly suggested liquid dehumidification. Renewable Energy; 33(9): 1989-1997.
30. Patek J, Klomfar J (2007) Thermodynamic properties of the LiCl-H2O system at vapor liquid equilibrium from 273 k to 400 K. International Journal of Refrigeration; 31(2): 287-303.
31. Saman W, Halawa E, Krause M (2007) Residential application of solar liquid desiccant cooling system in tropical countries of South East Asia. 12th international conference solar air-conditioning, Tarragona, Spain.
32. Jain S, Mithilesh K, Asati AK, et al. (2003) Drift and wetting characteristics of falling film absorber and regenerator, Proceedings of ACRECONF, Allied Publishers, N. Delhi; 16-25.
33. Ahmed, SY, Asan PIGS, AL-Farayedhi, AA (1998) Thermodynamic analysis of liquid desiccants. Solar Energy; 62(1): 11-18.
34. Lazzarin RM, Gasparella A, Longo GA (1999) Chemical dehumidification by liquid desiccants: theory and experiment. Int J of Ref,; 22(4): 334-347.
35. Liu XH, Jiang Y, Yi XQ (2009) Effect of regeneration mode on the performance of

liquid desiccant bed regenerator. Renewable Energy; 34(1): 209-216.

36. Yutong L, Hongxing Y (2008) Investigation on solar desiccant dehumidification process for energy conservation of air conditioning system. Applied Thermal Engineering; 28(10): 1118-1126.
37. Mago P, Goswami DY (2003) A study of the performance of a hybrid liquid desiccant cooling system using Lithium Chloride. ASME J Sol Energy Eng,; 125(1): 129-131.
38. Lazzarin R, Nalini L (2006) Air humidification – technical, health and energy aspects, Carel 2nd Edition.
39. Patil KR, Tripathi AD, Pathak G, et al. (1990) Thermodynamic properties of aqueous electrolyte solutions. vapour pressure aqueous solutions of LiCi, LiBr, and LiI. J Chem Eng Data; 35(2): 166-168.
40. Pietruschka D, Eicker U, Huber M, et al. (2006) Experimental performance analysis and modeling of liquid desiccant cooling systems for air conditioning in residential buildings. Int J of Ref,; 29(1): 110-124.
41. Abdul Wahab SA, Zurigat YH, Abu-Arabi MK (2004) Predictions of moisture removal rate and dehumidification effectiveness for structured liquid desiccant air dehumidifier. Energy; 29(1): 19-34.
42. Zurigat YH, Abu-Arabi MK, Abdul-Wahab SA (2004) Air dehumidification by triethylene glycol desiccant in a packed column. Energy Conversion and Management; 45(1): 141-155.
43. Yonggao Y, Xiaosong Z, Chen Z (2007) Experimental study on dehumidifier and regenerator of liquid desiccant cooling air conditioning system. Building and Environment; 42(7): 2505-2511.
44. Martin V, Goswami DY (2000) Effectiveness of heat and mass transfer processes in a packed bed liquid desiccant dehumidifier/regenerator. HVAC&R Research; 6(1): 21-39.
45. Factor HM, Grossman G (1980) Packed bed dehumidifier/regenerator for solar air conditioning with liquid desiccants. Solar Energy; 24(6), 541-550.
46. Chung TW (1994) Predictions of moisture removal efficiencies for packed-bed dehumidification systems. Gas Separation and Purification; 8(4): 256-268.
47. Martin V, Goswami DY (2000) Effectiveness of heat and mass transfer processes in a packed bed liquid desiccant dehumidifier/regenerator. HVAC&R Research; 6(1): 21-39.
48. Elsarrag E, Ali EEM, Jain S (2005) Design guidelines and performance study on a structured packed liquid desiccant air conditioning system. HVAC&R Journal; 11(2): 319-337.
49. Goswami DY, Frank K, Kreider JF (2000) Solar cooling and dehumidification, Principles of Solar Engineering. 2nd Edn Taylor and Fransis. Pp 289-290.
50. Chung TW, Luo CM (1999) Vapor pressure of the aqueous desiccants. J Chem Eng Data; 44(5): 1024-1027.
51. Jani DB, Mishra M, Sahoo PK (2016) Experimental investigation on solid desiccant – vapor compression hybrid air-conditioning system in hot and humid weather. Applied Thermal Engineering; 104: 556-564.
52. Jani DB, Mishra M, Sahoo PK (2016) Performance analysis of hybrid solid desiccant – vapor compression air-conditioning system in hot and humid weather of India. Building Services Engineering Research and Technology; 37(5): 523-538.
53. Gandidasan P (2004) A simplified model for air dehumidification with liquid desiccant. Sol Energy; 76(4): 409-416.
54. Zegenhagen MT, Ricart C, Meyer T, et al.

(2015) Experimental investigation of a liquid desiccant system for air dehumidification working with ionic liquids. Energy Procedia; 70: 544-551.

55. Jani DB, Mishra M, Sahoo PK (2016) Solid desiccant air conditioning – A state of the art review. Renewable and Sustainable Energy Reviews; 60: 1451-1469.
56. Lefevbre E, Fan L, Gagniere E, et al. (2015) Lithium bromide crystallization in water applied to an inter-seasonal heat storage process. Chemical Engineering Science; 133: 2-8.
57. Jani DB, Mishra M, Sahoo PK (2015) Performance studies of hybrid solid desiccant - vapor compression air-conditioning system for hot and humid climates. Energy and Buildings; 102: 284-292.
58. Popp S, Bosmann A, Wolfel R, et al. (2015) Screening of ionic liquid/H2O working pairs for application in low temperature driven sorption heat pump systems. ACS Sustainable Chemical Engineering; 3(4): 750-757.
59. Jani DB, Mishra M, Sahoo PK (2016) Performance prediction of rotary solid desiccant dehumidifier in hybrid air-conditioning system using artificial neural network. Applied Thermal Engineering; 98: 1091-1103.
60. Kudasheva A, Kamiya T, Hirota Y, et al. (2016) Dehumidification of air using liquid membranes with ionic liquids. Journal of Membrane Science; 499: 379-385.
61. Jani DB, Mishra M, Sahoo PK (2018) A critical review on application of solar energy as renewable regeneration heat source in solid desiccant – vapor compression hybrid cooling system. Journal of Building Engineering; 18: 107-124.
62. Moghaddam S (2016) A combined water heater dehumidifier and cooler (WDHC). U.S. Department of Energy; Building Technologies Office Peer Review.
63. Lowenstein A, Slayzak S, Kozubai E (2006) A zero carryover liquid-desiccant air conditioner for solar applications. Proceedings of ISEC 2006. Denver, CO, Paper No. ISEC2006-99079.
64. Jani DB, Mishra M, Sahoo PK (2018) Investigations on effect of operational conditions on performance of solid desiccant based hybrid cooling system in hot and humid climate. Thermal Science and Engineering Progress; 7: 76-86.
65. Chugh D, Gluesenkamp K, Adbelaziz O, et al. (2017) Ionic liquid-based hybrid absorption cycle for water heating, dehumidification, and cooling. Applied Energy; 202: 746-754.
66. Fekadu G, Subudhi S (2018) Renewable energy for liquid desiccant air conditioning: a review. Renewable and Sustainable Energy Reviews; 93: 364-379.
67. Griffiths WC (1980) Use of liquid sorption dehumidification to improve energy utilization of air systems. ASHRAE Transactions; 86(2): 33-39.
68. Kim YJ, Kim S, Joshi YK, et al. (2012) Thermodynamic analysis of an absorption refrigeration system with ionic-liquid/refrigerant mixture as a working fluid. Energy; 44(1): 1005-1016.

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