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Performance Review of Aqueous Calcium Chloride Liquid Desiccant Based Air Dehumidifier for HVAC Applications: A Review

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Abstract

The exponentially increasing need of human comfort in area of conditioned air has given giant thrust in energy consumption, specifically electrical energy, to run air conditioning equipments used in home or industry. Energy demand depletes the fossil fuel reservoir, affects the climate changes adversely and hence it is a matter of utmost concern to save the both. It is becoming almost inevitable to use air conditioning/cooling equipments in summer season in tropical region of the world. Calcium Chloride ($CaCl_2$) is one of the most economical liquid desiccants and used in many ways to reduce the latent heat content of air. In this paper, a review of calcium chloride based air dehumidifier done with insight in basic cycles of working, properties as a liquid desiccant and methods of use in practice for HVAC applications. In addition, the performance review of the calcium chloride based air dehumidifier for HVAC applications since its inception to the recent research going on it concisely given with key effects in its performance parameters to help understand the progress and trends of use.

It is evident from the given performance review that calcium chloride based air dehumidifier has progressed well from its simple form of working and experimented in different conditions with and without internal cooling of air dehumidifier in the field of air conditioning. However, there is scope of improvement to satisfy the unmated demand of performance and to accommodate into its fully developed form to take its place in day to day need of air conditioning in place of conventional vapor compression system.

Keywords- *Heating Ventilation and Air Conditioning (HVAC), Liquid Desiccant Based Air Dehumidifier (LDAD), Hybrid Desiccant Based Air Conditioning (HDBAC), Calcium Chloride ($CaCl_2$), Energy, Latent Heat, Sensible Heat.*

I. INTRODUCTION

It is self evident that electrical power consumption has been increasing significantly and has reached to the peak of all the other energy consumptions forms. The average temperature range over the year in building can be expected between temperature ranges of 12°C to 44°C in average in India [1]. Therefore, it is likely to have increased use of air conditioning specifically during hot and humid climate conditions. The contribution of power consumption for running the conventional vapor compression type air conditioning equipments in domestic/commercial sector is as high as 30 to 40 % and highest among all remaining type of energy consuming equipments used in domestic/commercial sector [1]. It directly correlates the consumption of fossil fuels, which in turn increases the green house gases and hence global warming of the environment. In near future, if the price of fossil fuels shoots very high due to fast depletion of it, then it is almost impossible to use the dependent air conditioning equipment by the average and below average class of consumers. By the time ahead, if the reservoirs of the fossil fuel are exhausted too much then there must be an economic alternative option of having conditioned air to have comfort climate to inhabitant of hot and humid climate of tropical region of the planet earth.

Desiccant in different forms have been used vastly in industry for dehumidification of air and proved economic. Desiccant dehumidification air-conditioning systems have excellent potential for cost-effective application in commercial buildings located in hot, humid climates. Hybrid liquid desiccant/vapor compression air-conditioning systems, in particular, are promising because they take advantage of the high efficiency for heat transfer inherent in vapor-compression systems and the high mama transfer potential of the liquid desiccants. However, to be cost effective, hybrid systems must provide operational savings over competing vapor compression air-conditioning systems and/or be less costly to manufacture. In the hybrid air conditioning system, a desiccant is circulated between the evaporator and condenser of a vapor- compression air conditioner providing both operational and first-cost savings. Continuing analytical work at The University of Texas has shown potential first-cost savings resulting in a 34% reduction in the exchange area for both the evaporator and condenser and a 25% reduction in the required compressor capacity. Additionally, electric power drawn by the compressor is expected to drop by 25%, resulting in savings on electric utility bills. These savings are possible without sacrificing cooling efficiency or thermal comfort [2].

The different types of desiccants in many forms are used to dehumidify air. The desiccants are natural or synthetic substances capable of absorbing or adsorbing water vapor due to difference of water vapor pressure between the surrounding air and the desiccant surface. They are available in both liquid and solid states. Each of liquid and solid desiccant systems has its own advantages and shortcomings. In addition of having lower regeneration temperature and flexibility in utilization, liquid desiccant have lower pressure drop on air side. Solid desiccant are compact, less subject to corrosion and carryover. Commonly used desiccant materials include lithium chloride (LiCl), lithium bromide (LiBr), triethylene glycol (TEG), calcium chloride ($CaCl_2$), silica gels, aluminium silicates (zeolites or molecular sieves), aluminium oxides etc.

Calcium Chloride is one of the most potent moisture absorbing compounds found in nature. As the second most commonly occurring substance in seawater next to salt, calcium chloride is also non-toxic and environmentally friendly. Calcium Chloride dissolves into a liquid brine partially due to the fact that it is able to attract several times its own weight in water. At a relative humidity (RH) of only 50%, calcium chloride's moisture absorption is 150% its weight in water. Its absorption increases exponentially as RH rises, to 600% at 85% RH.

II. COMMERCIAL DEVELOPMENT OF LIQUID DESICCANT TECHNOLOGY

Desiccant air conditioning technology developed in the United States before the advent of vapor compression cooling. The Kathabar liquid desiccant system, introduced in 1910, was the first air conditioning use of a technology that had previously been used largely in chemical process and petroleum refining operations. During the 1930's, the Niagara Blower Company began using a desiccant solution (Triethylene Glycol) as a means of removing frost from evaporator coils in refrigeration systems. The system had dehumidification as well as defrosting capabilities, and continues in use today. Kathabar produced the first cooling and dehumidifying desiccant system in 1937 for a large central system used for an industrial plant [16]. In 1940, however, an article in the Cleveland Press (Jan. 22, 1940, "Today's Business - Bryant's New Product") indicates that manufacturers of desiccant equipment retained an interest in comfort-conditioning markets. During the 1950's, Kathabar successfully applied their liquid desiccant system to hospital ventilation systems. This application takes advantage of the bactericidal characteristics of lithium chloride to scrub the air free of microorganisms in addition to removing excess humidity and delivering air at a controlled temperature. In liquid systems, further improvements were made to the Kathabar system during the 1970's, reducing the mass and pressure drop of the contact media for the desiccant [4].

III. WORKING PRINCIPLE AND DIFFERENCE BETWEEN CONVENTIONAL VAPOR COMPRESSION CYCLE AND SIMPLE LIQUID DESICCANT AIR CONDITIONING CYCLE

The figure given below shows the air conditioning processes of traditional HVAC system and desiccant cooling system (Fig. 2.1) and their thermal processes at different stage of processes (Fig. 2.2). Point 1 represent inlet condition of atmospheric air passing through heat and mass exchanger and thereby giving a part of its sensible heat content to returning air from the working room at point 6 and so reaches at state 2. From there it passes through cooling coil (i.e. evaporator) and its temperature is reduced to or lowers than dew point temperature and moisture is condensed in the cooling unit to have latent heat removal and hence extreme cooling of the air to come out at the state 3. To have comfortable atmosphere inside the working room, the air is heated at point 4 by passing through a heater which in turn consumes energy to restore the appropriate temperature of air and then the air is sent to working room to have comfortable environment. While on the contrary in desiccant air conditioning system; the liquid desiccant air dehumidifier is used to lower the latent heat content of the inlet air (state-2') by having absorption of the vapor of air by the cold liquid desiccant without lowering the temperature of air to or below its dew point temperature (state-3'). Also there is no requirement of heater in liquid desiccant system which is directly an energy conservation.

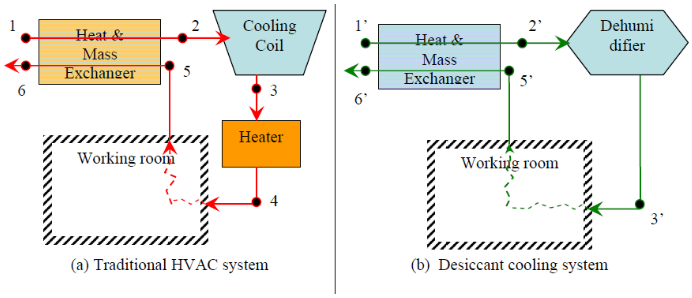


Figure 3.1 Air conditioning processes: (a) Traditional HVAC (b) Desiccant cooling with efficient heat/mass recovery [3].

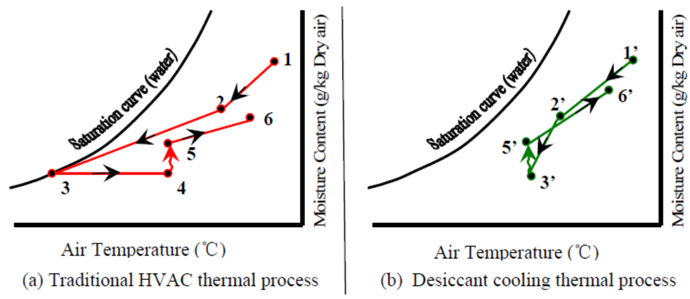


Figure 3.2 Thermal processes: (a) Traditional HVAC (b) Desiccant cooling with efficient heat recovery [3]

The primary difference between traditional HVAC vapour compression air conditioning system and liquid desiccant cooling system lies in method of removing latent heat load from air. In vapour compression air conditioning system the air is cooled below its dew point temperature to condense out the moisture from the air and thereby lowering/removing the latent heat load from the air, while in liquid desiccant based air conditioning system the moisture is absorbed by the cold liquid desiccant by virtue of vapour pressure difference between concentrated liquid desiccant and air and hence decreases moisture from the air without getting its temperature lower than its dew point temperature.

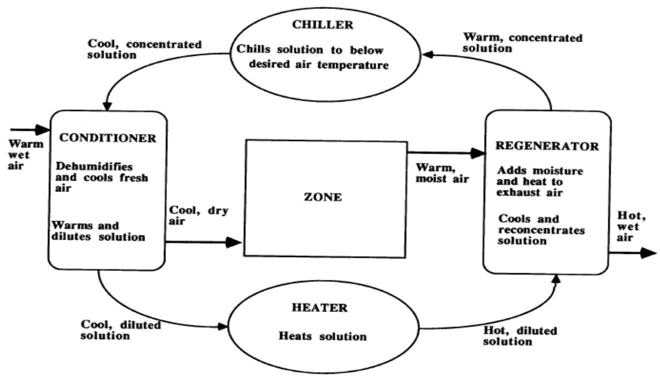


Figure 3.3 Basic System Configuration of Liquid Desiccant Cooling and Dehumidification System [11]

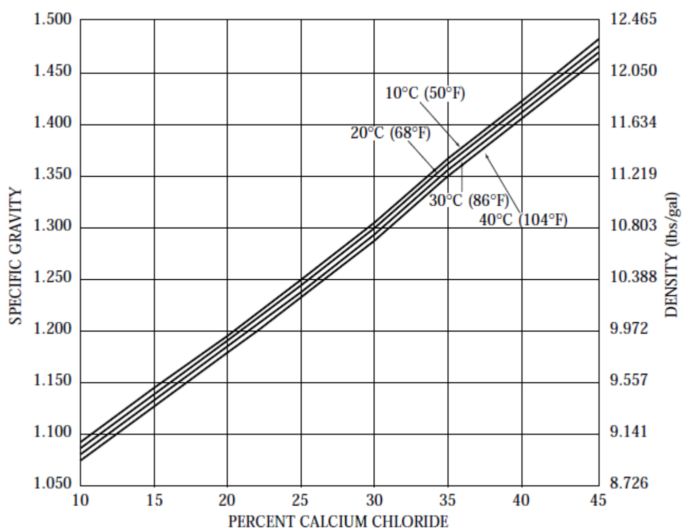
3.1. Major difference between traditional HVAC and liquid desiccant air conditioning system:

- The vapour content from the air (i.e. latent head load) is absorbed by attaining dew point temperature in traditional HVAC system; while in liquid desiccant system it is accomplished by absorption of vapour due to vapor pressure difference between cold liquid desiccant and inlet air without attaining dew point temperature of air.
- There should be continuous decrement of air temperature in traditional HVAC system, which is not there in liquid desiccant system.
- Electrical heater may be required to restore air in comfort zone in traditional HVAC system, which intern increases overall energy consumption of the system. However, it is not required at all in liquid desiccant system, which is direct saving of input energy.
- The exact controlling of vapour content of air is very much difficult in traditional HVAC system whereas it is very convenient and economic to control exact content of moisture of air by just varying liquid desiccant flow rate and/or concentration in liquid desiccant system.
- Simple arrangement of air conditioning system components is there in traditional HVAC system, which is somewhat complex in liquid desiccant system of air conditioning.
- The temperature and moisture control occurs together in traditional HVAC system; where as individual treatment of temperature and moisture control is possible and very convenient in liquid desiccant system; which is one of the major plus point of it in such type of requirement of individual controlling of temperature and moisture content of air.
- Continuous use of traditional HVAC system gives consistent performance and its performance decreases with intermittent or fluctuating use of it. However, liquid desiccant system may be used intermittently without much affecting its capacity and performance of the system.
- Initial cost is lower and running cost is higher in traditional HVAC system; while in liquid desiccant system, the initial cost is higher and running cost is lower.
- There is issue of higher pressure and lower pressure maintenance in traditional HVAC system, which is not at all required in liquid desiccant system.
- Traditional HVAC system used CFCs, HCFCs and other hazardous and costly gases. While liquid desiccant system uses natural or synthetic organic compounds of salts as a liquid desiccant which are cheaper than the CFCs, HCFCs gases.
- Due to use of liquid desiccants, there is greater chance of corrosion of metallic component of the system. Which is almost absent in traditional HVAC system.
- Microbial cleaning of air is only possible in liquid desiccant technology.

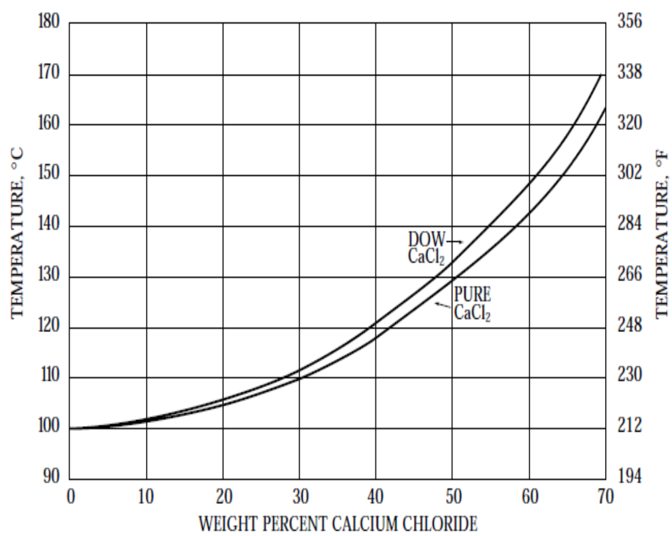
IV. PROPERTIES AND CHARACTERISTICS OF CALCIUM CHLORIDE ($CaCl_2$) AS A LIQUID DESICCANT

- The basic characteristics required in any of the liquid desiccant are:
- High affinity with water vapor.
- Chemical and physical stability over many cycles.
- Ability to hold large weight fractions of water.
- Ability to separate water vapor from other constituents.
- Ability to attract water vapor at desired partial pressures.

Liquid calcium chloride manufactured in general range of concentrations of 28% to 42% and 45% for the use in HVAC applications. The commercial grades of calcium chloride contain other trace elements and compounds manufactured within the limits defined by The American Society for Testing and Materials (ASTM) Standards. However, for the theory points of view the, properties of pure calcium chloride & calcium chloride –water solution has been given below.



Graph: 4.1 Specific Gravity vs. % $CaCl_2$ [5]

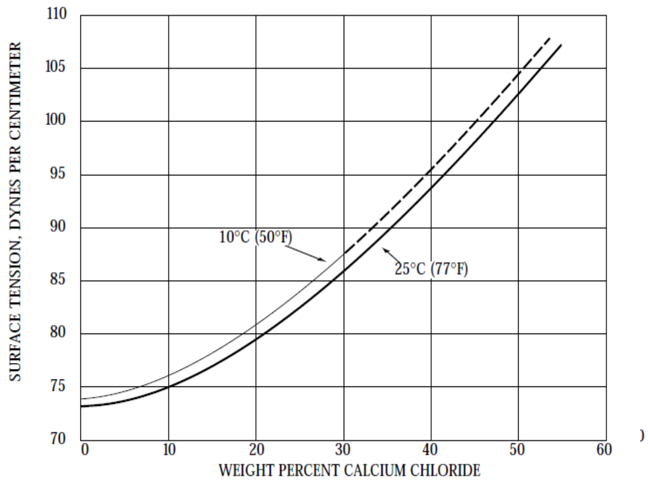


Graph: 4.2 Boiling Points of $CaCl_2$ [5]

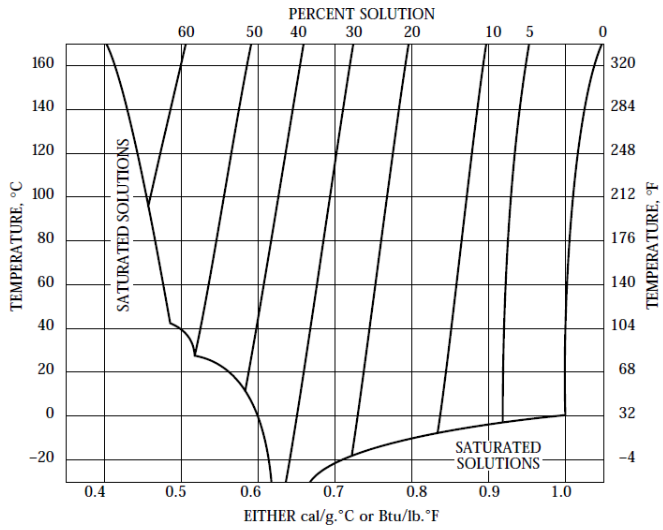
Table: 4.1 Properties of $CaCl_2$ hydrates [5]

Property	$CaCl_2 \cdot 6H_2O$	$CaCl_2 \cdot 4H_2O$	$CaCl_2 \cdot 2H_2O$	$CaCl_2 \cdot H_2O$	$CaCl_2$
Composition (% $CaCl_2$)	50.66	60.63	75.49	86.03	100
Molecular Weight	219.09	183.05	147.02	129	110.99
Melting Point[1] (°C)	29.9	45.3	176	187	773
(°F)	85.8	113.5	349	369	1424
Boiling Point[2] (°C)	—	—	174	183	1935
(°F)	—	—	345	361	3515
Density at 25°C (77°F), g/cm³	1.71	1.83	1.85	2.24	2.16
Heat of Fusion (cal/g)	50	39	21	32	61.5
(Btu/lb)	90	70	38	58	110.6
Heat of Solution[3] in H_2O (cal/g)	17.2	–14.2	–72.8	–96.8	–176.2
(to infinite dilution) (Btu/lb)	31.0	–25.6	–131.1	–174.3	–317.2
Heat of Formation[3] at 25°C (77°F), kcal/mole	-623.3	–480.3	–335.58	–265.49	–190.10
Heat Capacity at 25°C (77°F), cal/g.°C or Btu/lb.°F	0.34	0.32	0.28	0.20	0.16

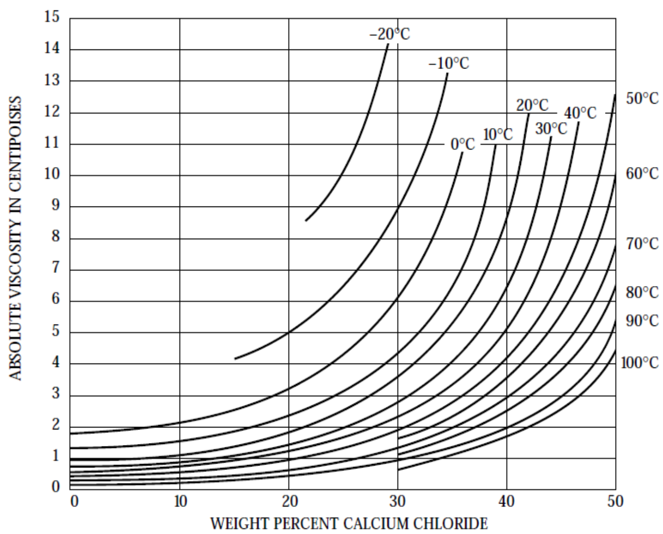
[1]Incongruent melting point for hydrates.
[2]Temperature where dissociation pressure reaches one atmosphere for hydrates.
[3]Negative sign means that heat is evolved (process exothermic).



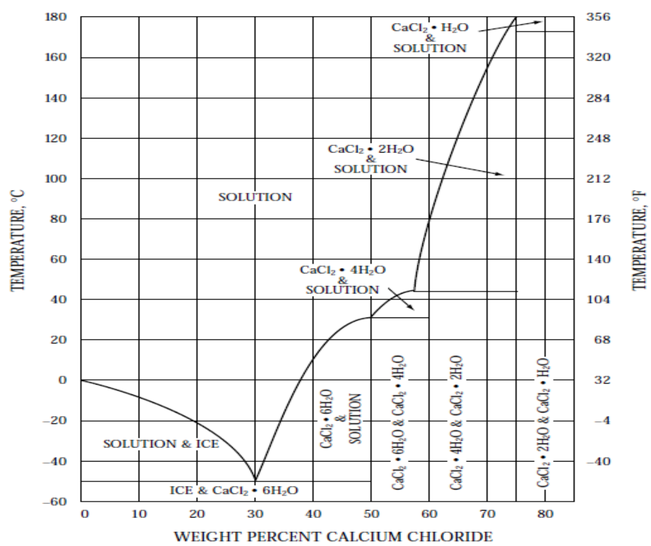
Graph: 4.3 Surface Tension of Pure $CaCl_2$ Solutions [5]



Graph: 4.4 Specific Heat of Aqueous $CaCl_2$ [5]

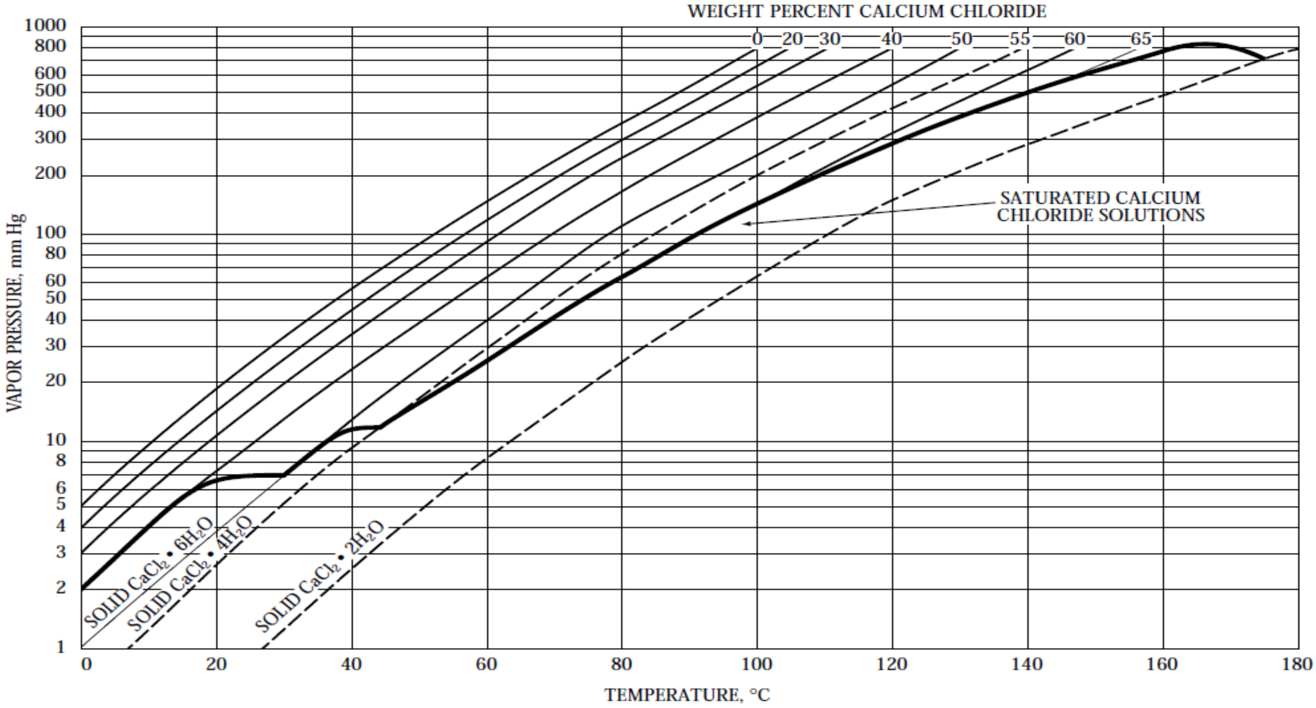


Graph: 4.5 Viscosity of Pure $CaCl_2$ Solution [5]



Graph: 4.6 Phase Diagram of $CaCl_2$ Solution [5]

Graph: 4.7 Vapor Pressure of $CaCl_2$ Hydrates and Solutions [5]



V. METHODS OF CONFIGURATIONS OF LIQUID DESICCANT BASED AIR DEHUMIDIFIER USED IN PRACTICE

5.1. Based on Direction of Interaction Between Air and Liquid Desiccant Used In Practice for Liquid Desiccant Based Air Dehumidifier are:

(i) Parallel Flow:

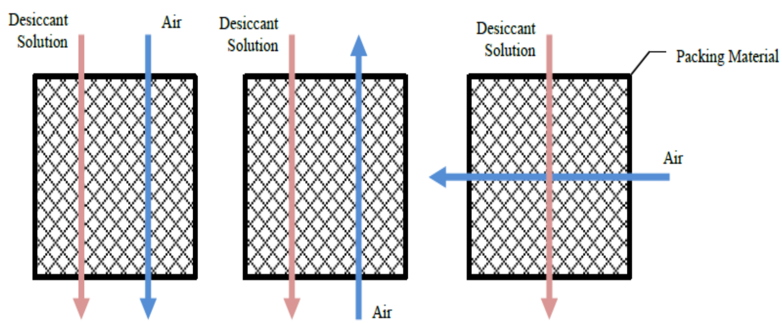
In parallel flow configuration, air and desiccant solution flow parallel with each other in downward direction. Here initially at the entry point, the vapour pressure difference is large between air and desiccant solution which then go on decreasing as flow proceeds to downward, which affects the effectiveness and hence economy of the dehumidification process. It is one of the simples method to have easy and economical configuration. Since, the flow direction is same and downward, so there is no major issue related to carry over of desiccant solution with airflow.

(ii) Counter Flow:

In counter flow, air and desiccant flow in opposite direction. Preferable air in upward direction and desiccant solution in downward direction with the help of gravity. In this configuration, there is overall large vapor pressure difference between air and desiccant solution compared to any other method and hence it is one of the most effective, economical and compact arrangement for dehumidification of air. But slight carryover of desiccant may happen in this configuration due to upward motion of air.

(iii) Cross Flow:

In cross flow configuration, air and desiccant flow in perpendicular direction with respect to each other. Generally, desiccant in downward direction and air in perpendicular horizontal direction with respect to desiccant. There is problem of carryover of desiccant with air due to cross flow between them. But advantage is that there is good interaction and more surface contact between them so as to have better effectiveness.



(i) Parallel Flow (ii) Counter Flow (iii) Cross Flow

Figure: 5.1 Configuration of Air Dehumidifier Based on Direction of Interaction Between Air and Liquid Desiccant

5.2. Based on Method of Interaction Between air And Liquid Desiccant Used in Practice for Liquid Desiccant Based Air Dehumidifier are:

(i) Packed Tower:

In a packed-tower dehumidifier the liquid is distributed over the packing and flows downwards in thin films covering the extended surface of the packing. Air passes in the opposite direction through the packing providing a counter-flow arrangement for mass transfer. The packing may be made of glass, ceramic, metal or plastic in various shapes and sizes. A modern lightweight cooling tower type packing made up of layers of corrugated plastic sheets combines good mass transfer rates with an air pressure drop generally lower than for other types of packing.

A packed tower offers the advantages of compactness, low pressure drop in the liquid circuit and high mass transfer effectiveness. The disadvantages of the packed tower are that the air pressure drop through the packing is generally high and that the isothermal dehumidifying process is not always feasible. There is also a possibility of contamination of the packing with airborne dust at times of no liquid flow. This could however be overcome by air filtration, which in any case should always be provided in an air conditioning system.

(ii) Spray Chamber:

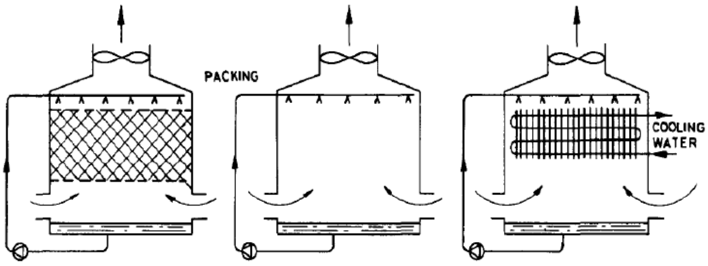
In a spray chamber dehumidifier, the liquid is atomized into the air stream by means of high pressure nozzles. The large surface area of the dispersed liquid serves to enhance the mass transfer rate resulting in good dehumidifying effectiveness. The advantage of a spray chamber is the low air pressure drop, but this is offset by the requirement for high pressure at the spray nozzles for good atomization. Other disadvantages are its greater bulk compared to the packed tower and the difficulty of arranging for isothermal operation although a certain amount of cooling can be provided by a heat exchanger in the sump or in the liquid circulation line.

(iii) Sprayed Coil:

A sprayed-coil dehumidifier combines two processes of the desiccant system namely, dehumidification and sensible cooling in one piece of equipment. The liquid desiccant is distributed over a finned type heat exchanger and flows downwards in thin films over the tubes and fins of the heat exchanger. The wetted surface of the heat exchanger provides the necessary contact area between the liquid and the air flowing through the heat exchanger. Cooling water is pumped through the heat exchanger tubes and removes the heat of sorption, resulting in an approximately isothermal process.

The advantages of the sprayed-coil dehumidifier include: compact size, high mass transfer effectiveness, low pressure requirements for liquid distribution, low air pressure drop as compared to a packed tower with separate sensible heat exchanger and the inherent isothermal type of operation.

The disadvantage, like in a packed tower, is the possibility of contamination by airborne dust at conditions of no liquid flow if insufficient air filtration is provided in the system.



(i) Packed Tower (ii) Spray Chamber (iii) Sprayed Coil

Figure: 5.2 Configuration of Air Dehumidifier Based on Method of Interaction Between Air and Liquid Desiccant [19]

5.3. Based On Method of Arrangement of Different Components in Liquid Desiccant Cycle.

5.3.1 Liquid Desiccant Ventilation System:

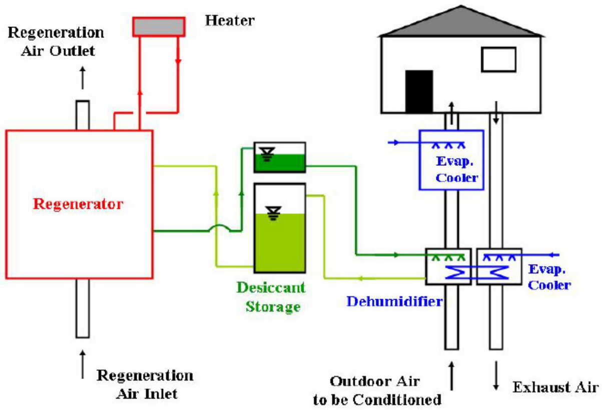


Figure 5.3 Liquid Desiccant Ventilation System [6]

5.3.2 Closed Absorption System:

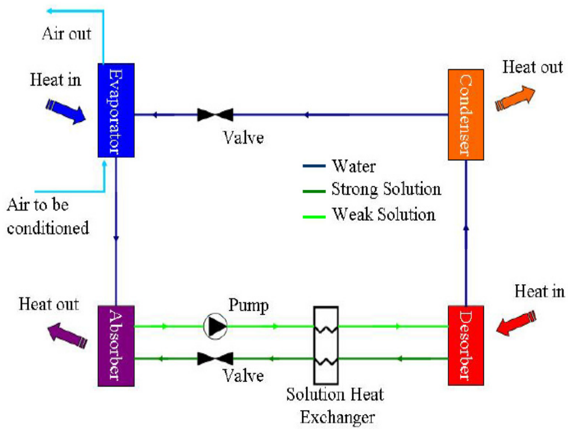


Figure 5.4 Closed Absorption System [6]

5.3.3 Open Absorption System:

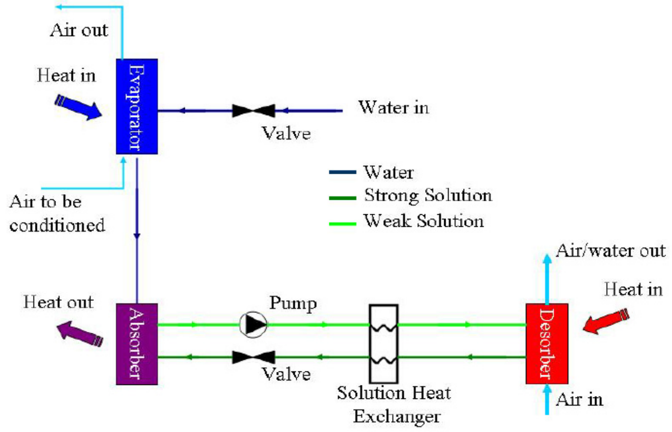


Figure 5.5 Open Absorption System [6]

5.3.4 Closed Desorber System:

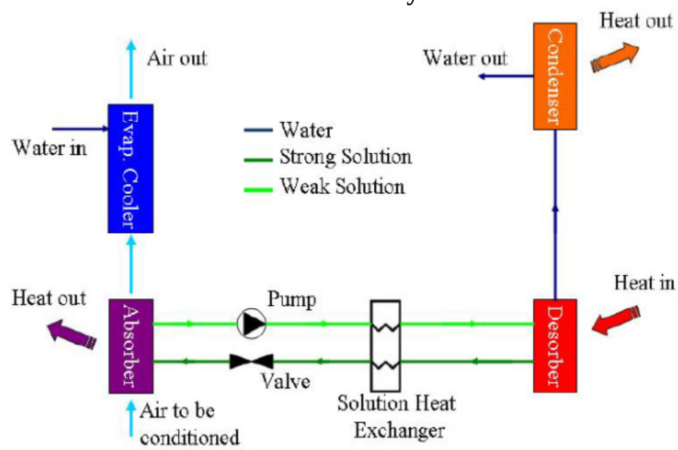


Figure 5.6 Closed Desorber System [6]

5.3.5 Hear Recovery Desiccant Cooling System:

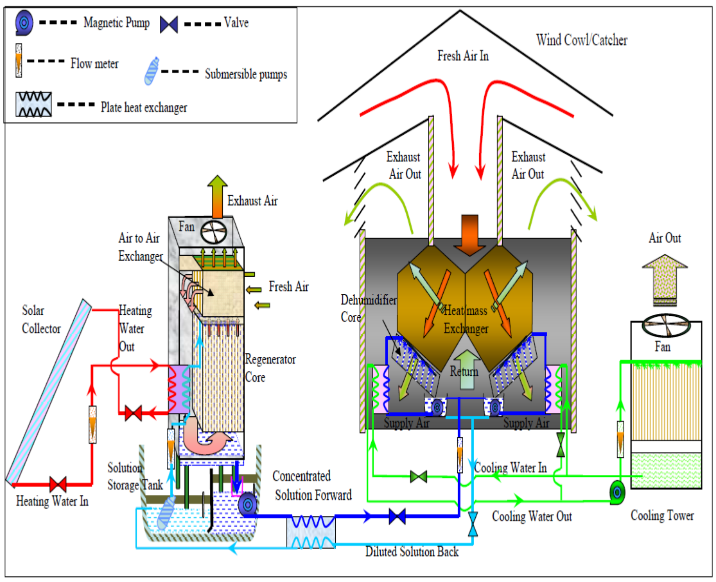


Figure 5.7 Heat Recovery Desiccant Cooling System [3]

5.3.6 Hybrid Vapour Compression/Liquid Desiccant Air Conditioning System:

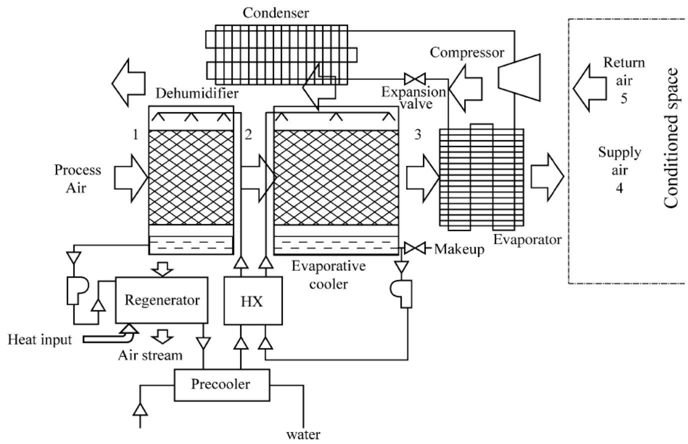


Figure 5.8 Hybrid Vapour Compression/Liquid Desiccant Air Conditioning System [12]

VI. PERFORMANCE REVIEW OF AQUEOUS CALCIUM CHLORIDE ($CaCl_2$) LIQUID DESICCANT BASED AIR DEHUMIDIFIER

1. **Researcher/s:** Ozer A. Arnas, Troy M. McQueen (1984) [28]
   Study Type: Experimental
   LD Proportion and Type:
   Aqueous 42% Concentration $CaCl_2$ solution by weight.
   LDAD System: Cross flow/ Counter flow, internally cooled, finned tube, spray type liquid desiccant air dehumidifier**.**
   Result/s:
   – The solution at mass flow rate of 1.26 liter/second absorbs 30 kg/hr of water from the air stream, assuming an approach factor of 80 %.
   Remark/s: The existing split package air conditioning system was combined with desiccant air-conditioning unit with a waste heat and solar heat reclaim component.

2. **Researcher/s:** Howell, J. R., Peterson, J. L (1986) [9]
   Study Type: Experimental
   LD Proportion and Type: Applicable to any type of liquid desiccant in general.
   LDAD System: Hybrid liquid desiccant & vapor compression cycle
   Result/s:
   – Compressor power consumption reduces by 25%.
   Evaporator & condenser area reduces by 34%.
   Remark/s: As compared to standard vapor compression cycle.

3. **Researcher/s:** Ertas et al. (1992) [7]
   Study Type: Experimental
   LD Proportion and Type: Mixture of LiCl and $CaCl_2$ solution.
   LDAD System: ---
   Result/s:
   – As the fraction of $CaCl_2$ to LiCl increases 0% to 50%, the equilibrium vapor pressure for the solution more closely matches the value for pure LiCl.

- The equilibrium vapor pressure for the 50/50 mixture is a 71/29 weighted average of the values for solutions of pure LiCl and pure $CaCl_2$.
- The 43% solution of the 50/50 mixture would behave in the LDAC the same as a 40% solution of pure LiCl.
- The 43% $CaCl_2$ solution behaves like a 34% LiCl.

Remark/s: However, complete design study is needed to exactly predict the performance with 50% ($CaCl_2$)-50 % (LiCl) solution to check its attractiveness.

4. **Researcher/s:** A. Rahamah, M.M.Elsayed, N.M.Al-Najem (1998) [18]
Study Type: Numerical/ Parametric
LD Proportion and Type: Aqueous 60% Concentration $CaCl_2$ solution by weight
LDAD System: Falling liquid desiccant film and air in parallel flow.
Result/s:
- Low air flow rates produce better dehumidification and cooling processes.
- Increasing the channel height leads to better cooling and dehumidification processes for the outlet air; however, the rate is decreased.
- The dehumidification process can be enhanced by decreasing the inlet water concentration in the desiccant solution to certain levels to avoid salt crystallization in the solution.

Remark/s: The control volume approach is used to predict the outlet conditions for both the air and the desiccant solution.

5. **Researcher/s:** Saman and Alizadeh (2002) [7]
Study Type: Experimental
LD Proportion and Type: Aqueous 40% Concentration $CaCl_2$ solution by weight
LDAD System: LD sprayed as counter flow, 0.1 L/G ratio
Result/s:
- 0.75 heat/mass effectiveness could be achieved at a process airflow of 0.3 kg/s

Remark/s: Heat/mass effectiveness: the measured enthalpy change for the process air / the maximum theoretical limit.

6. **Researcher/s:** A. Ali, K. Vafai, A.-R.A. Khaled (2003) [10]
Study Type: Parametric/ Numerical
LD Proportion and Type: Aqueous 60% Concentration $CaCl_2$ solution by weight
LDAD System: Cross flow, falling film type dehumidifier
Result/s:
- Low air Reynolds number provides better dehumidification and cooling for the exit air conditions.
- Solution Reynolds number has a minimal effect on dehumidification and cooling processes of the air.
- An increase in the height and length of the channel offers better dehumidification and cooling for air exit conditions.
- A decrease in the width of the channel enhances the dehumidification and cooling processes for the exit air conditions.
- An increase in Cu-volume fraction and thermal dispersion effects enhances the heat and mass transfer and results in a better dehumidification and cooling processes for the air. It also results in dynamically stable solution.

Remark/s: Cu-ultrafine particles added to enhance heat and mass transfer

7. **Researcher/s:** Scott Feyka, Kambiz Vafai (2007) [8]
Study Type: Parametric
LD Proportion and Type: Aqueous $CaCl_2$ solution
LDAD System: Cross flow, falling film type dehumidifier
Result/s:
- Relative humidity of inlet air reduces up to 22%.
- 18 to 22% higher COP than Chiller Cycle for the same temp. difference.
- Liquid desiccant cooling is relatively ineffective for required temperature reductions above 20◦C.

Remark/s: Heat/mass effectiveness: the measured enthalpy change for the process air / the maximum theoretical limit.

8. **Researcher/s:** M.M. Hammad et. al. (2008) [22]
Study Type: Numerical
LD Proportion and Type: Aqueous $CaCl_2$ solution with concentration of: 20%, 25%, 35%, 45%.
LDAD System: Shell type, flooded liquid desiccant shell with zigzag staggered arrangement of copper cold water tubes in the shell with co-current flow of air in the form of bubbles and liquid desiccant from the bottom
Result/s:
- The air humidity ratio decreases along the dehumidifier height with increasing of the desiccant solution concentration, but with decreasing of desiccant solution temperature.
- The desiccant solution moisture content decreases along the dehumidifier height with the increasing of the desiccant solution temperature and the mass flow rate, but with decreasing of the inlet humidity ratio.
- The air temperature decreases along the dehumidifier height with the increasing of both of the desiccant solution concentration and the inlet humidity ratio, but with decreasing of the desiccant solution inlet temperature.
- The desiccant solution temperature decreases along the dehumidifier height with the decreasing of any of the desiccant solution mass flow rate or the cooling water temperature, but with increasing of the desiccant solution concentration and is not affected with the inlet humidity ratio.
- Only about 40% of the dehumidifier height is enough to get the maximum performance of the dehumidifier and save both fixed and operating costs for this design.
- The desiccant solution moisture content gain increases with the increase of each of the desiccant solution concentration and the inlet humidity ratio, but it increases with the decrease of the desiccant solution temperature and the mass flow rate.

- The desiccant solution moisture content gain increases with increasing of the air Peclet number and as well as with the air to desiccant solution thermal conductivity ratio/ the air to desiccant solution specific heat ratio, but it increases with the decreasing of the equilibrium humidity ratio condition of the air in contact with the desiccant solution and the solution Peclet number.
- The air humidity ratio reduction decreases with the increase of the equilibrium air humidity ratio.
- Both of the humidity reduction ratio and the dehumidifier effectiveness decreases with the increase of the cooling water temperature and the liquid desiccant solution temperature.
- The inlet air temperature (the ambient air temperature) has insignificant effect on the dehumidifier performance indices. While the increase of the inlet air humidity ratio (ambient air humidity ratio) the humidity reduction ratio increases.
- The increase of the air flow rate leads to decrease in the two performance indices of the dehumidifier which are the humidity reduction ratio and the dehumidifier effectiveness.
- The increase of the liquid desiccant solution flow rate leads to an increase of the dehumidifier performance indices.
- As the solution to air mass flow rate ratio increases the performance indices increases.
- Both the performance indices increase with the increase of the liquid desiccant solution concentration. **Remark/s:** Results of numerical analysis have been validated at 25% & 35% concentration of $CaCl_2$ aqueous solution with the literature results of experimental studies.

9. **Researcher/s:** A.E. Kabeel (2010) [13]
Study Type: Experimental
LD Proportion and Type: Aqueous $CaCl_2$ solution
LDAD System: Cross flow, spray type dehumidifier
Result/s:
- The system effectiveness reached to 0.87 in the dehumidification and about 0.92 in the humidification process.
- A mass transfer coefficient of 28 kgs/1m^2 mm Hg at an air mass flow rate of 0.022 kg/s in the dehumidification process

Remark/s: Using an injected air through the liquid desiccant solution.

10. **Researcher/s:** N. Audah, N. Ghaddar, K. Ghali (2011) [21]
Study Type: Numerical/ Parametric
LD Proportion and Type: Aqueous 40% Concentration $CaCl_2$ solution by weight
LDAD System: Counter flow, packed beds, spray type dehumidifier
Result/s:
- A lower heat sink temperature at 17–18 ^{o} C with an additional solar collector would prove economically feasible.
- The optimal regeneration temperature increases with decreased heat sink temperature with values of 50.5 ^{o} C and 52 ^{o} C corresponding to sink temperatures of 19 ^{o} C and 16 ^{o} C.

Remark/s: This paper studies the feasibility of using a solar-powered liquid desiccant system to meet both building cooling and fresh water needs.

11. **Researcher/s:** Pradeep Patanwar, S.K. Shukla (2012) [27]
Study Type: Experimental
LD Proportion and Type: Aqueous 40% Concentration $CaCl_2$ solution by weight
LDAD System: Netlon mesh type, Cross flow, spray type dehumidifier
Result/s:
- The COP increases by 30 % compared with the same capacity of conventional VCS.
- The cooling effect required by Solar Liquid Desiccant Air Conditioning System is 30.5% lower than the conventional VCS for the conditioning of same mass flow rate of air.

Remark/s: The contacting device used in the absorber incorporates large surface density of 232 m^2/m^3 which is 10.5 % more than the conventional packing materials.

12. **Researcher/s:** Pradeep Patanwar, S.K. Shukla (2012) [27]
Study Type: Experimental/ Mathematical Modeling
LD Proportion and Type: Aqueous 35% concentration$CaCl_2$ solution
LDAD System: Counter-flow packed bed packed with polypropylene cascade ring, spray type liquid desiccant air dehumidifier
Result/s:
- The optimum inlet temperature should be more than 17 ℃ when the desiccant inlet temperature is 17 ℃ and desiccant concentration is 35 %.
- The optimum desiccant outlet concentration should be between 0.2 to 0.9.
- The optimum air flow rate should be between 1.5 m/s to 2.5 m/s if the desiccant flow rate assumed to be 0.2685 kg/s and inlet humidity ratio to be 14 g/kg.
- Increased air flow rate enhances the condensation of moisture and thus overall increases moisture removal rate.
- Increased inlet air temperature helps the desiccant solution to easily trap the moisture from humid fresh air and thus increases the effectiveness.
- Increased humidity also enhances condensation and thereby moisture removal rate.

Remark/s: The towers are made of up of fiber reinforced plastic (FRP) of thickness 4 mm and it has a constant height of 100 cm. Packing is done using polypropylene cascade ring of specific surface area 205 mm^2/mm^3 for a height of 30 cm.

13. **Researcher/s:** A. E. Kabeel, Ali M Almagar (2013) [14]
Study Type: Experimental
LD Proportion and Type: Aqueous $CaCl_2$ solution
LDAD System: Cross flow, spray type dehumidifier

Result/s:

- The system effectiveness reached 0.75 in the dehumidification process.
- Mass transfer coefficient reached to 28 kg/sm2 mm-hg at flow rate equals 0.022 x 10-3 kg/s in the dehumidification process..

Remark/s: The air is injected through the desiccant liquid at different air flow rates.

14. **Researcher/s:** Nanda Kishore P.V.R, Dilip D (2013) [15]

Study Type: Experimental

LD Proportion and Type: Aqueous $CaCl_2$ solution

LDAD System: Packed column packed with random packing in which air and the desiccant solution flow in a counter flow manner.

Result/s:

- When mass air flow rate (G) decreases keeping desiccant flow rate a constant then, humidification of air stream increases.
- Dehumidification in the absorber increases as air flow rate increases for any process desiccant inlet temperature.

Remark/s: The packed bed consists of polypropylene intalox saddle.

15. **Researcher/s:** Thosapon Katejanekarn, Watanyoo Panangnuwong (2013) [17]

Study Type: Experimental

LD Proportion and Type: Aqueous 40% Concentration $CaCl_2$ solution by weight

LDAD System: Counter-flow packed bed spray type with a diameter of 0.68 m and a height of 1.90 m.

Result/s:

- As the desiccant flow rates of 0.02 and 0.12 kg/s, the moisture removal rate increased with the increase of the air flow rate until a certain point then it became nearly constant or gradually decreased.
- The moisture removal rate increased with the increase of the desiccant flow rate.
- The moisture removal rate increases with the decrease of the temperature of the fluids.
- At the desiccant flow rates of 0.02 and 0.12 kg/s, the effectiveness increased with the increase of the air flow rate until a certain point then it became nearly constant or gradually decreased because of the less contact time between the air and the desiccant.
- The dehumidification effectiveness increased with the increase of the desiccant flow rate.
- The effectiveness increases with the decrease of the temperature of the fluids.

Remark/s: Outside wall insulated with 0.15m fiberglass. Inside filled with 25-mm Pall ring packings that formed a 0.50-m packed bed.

16. **Researcher/s:** Jagjit Singh, Rakesh Kumar (2013) [24

Study Type: Experimental

LD Proportion and Type: Aqueous 37.4 % concentration $CaCl_2$ solution by weight

LDAD System: counter-flow structured packing bed column, spray type liquid desiccant air dehumidifier (60cm x 30cm x 90cm).

Result/s:

- With increase of desiccant mass flow rate from 0.02 kg/s to 0.08 kg/s and with increase of inlet air flow rate 0.00091 kg/s to 0.00117 kg/s the moisture absorption rate increases from 3 gm/kg to 7.5 gm/kg.
- With increase of desiccant mass flow rate from 0.02 kg/s to 0.08 kg/s and with increase of inlet air flow rate 0.00091 kg/s to 0.00117 kg/s the dry bulb outlet temperature of air increase from 34 0C to 41 0C.
- With decreases of desiccant solution temperature from 40 0C to 36 0C and with the decrease of inlet air mass flow rate from 33 to 20 gm/sec, the rate of mass of water evaporation increase from 0.0025 gm/s to 0.009 gm/s.
- With decreases of desiccant solution temperature from 40 0C to 36 0C and with the decrease of inlet air mass flow rate from 33 to 20 gm/sec, moisture absorption rate increases from 3 gm/kg to 7.5 gm/kg..

Remark/s: The packing consisted of arrays of plates stacked in the column and oriented 90ºto each other. Three densities were used 150 m^2/m^3.

17. **Researcher/s:** S. Bouzenada, T. Salmon, L. Fraikin, A. Kaabi, A. Léonard. (2014) [16]

Study Type: Experimental

LD Proportion and Type: Aqueous $CaCl_2$ solution & $CaCl_2.2H_2O$ aqueous solution

LDAD System: The air is introduced horizontally into the Conditioning Drying Oven apparatus; and uniformly distributed over its whole surface to achieve the flow conditions while the desiccant solution is placed on plate inside of the apparatus.

Result/s:

- The mass transfer potential of CaCl2 solution is better than that of CaCl2.2H2O solution in the same desiccant mass flow rate condition due to water molecules present in the letter salt.
- Then the CaCl2 is able to absorb more moisture in the cycle of the LDCS system.

Remark/s: The Calcium chloride desiccant and Calcium chloride dehydrate were used as desiccant.

18. **Researcher/s:** J.R. Mehta, H.C.Badrakia (2014) [25]

Study Type: Experimental

LD Proportion and Type: Aqueous 41 % concentration $CaCl_2$ solution by weight

LDAD System: Cross flow, Internally cooled, finned tube, spray type liquid desiccant air dehumidifier. (VCS evaporator)

Result/s:

- Humidity ratio increases from 16.8 to 19.4 kg/kgda (increase by 15.5%), the moisture removal rate (MRR) increases by 52.3%.
- Total cooling increased by 12.6%.
- Latent cooling increased by 46.7%.
- Sensible cooling reduced by 13.9% when humidity ratio of inlet air increased.
- When the moisture removal rate increases, latent heat generation increases.
- Air velocity is reduced from 1.28 to 0.85 m/s (reduction by 33.6%), change in humidity ratio of air increases from 8.4 to 9.2 kg/kgda.

– MRR reduced by 27.3% due to reduced air flow rate.
– Capacity of the cooling coil could be increased by around 32% at 22 oC cooling water temperature and 41% aqueous calcium chloride as LD.
– Even at 18 oC, though total cooling rate increased by around 6%, latent cooling increased by around 36%.
– Lowering the velocity marginally improves moisture and enthalpy effectiveness but reduces the capacity of the coil significantly.

Remark/s: The internally cooled contacting device consists of a four row finned tube flooded water type coil.

19. **Researcher/s:** M.M. Bassuoni (2014) [26]
Study Type: Experimental
LD Proportion and Type: Aqueous 32% , 36%, 40%, 44% concentration $CaCl_2$ solution by weight
LDAD System: Cross flow, Internally cooled, finned tube, spray type liquid desiccant air dehumidifier. (VCS evaporator).
Result/s:
– The coefficient of performance of the proposed system is found to be 54% greater than that of VCS with reheat at typical operating conditions.
– The HDBAC system integrated with a 5.27 kW conventional VCS can replace a VCS with reheat with a cooling capacity of 9.13 kW.
– The coefficient of performance and the specific moisture removal of the proposed system are both increased with increasing both air and desiccant solution flow rates.
– An increase of strong solution concentration will increase both COPa and SMR.
– The COPa increases and SMR decreases by increasing the temperature of the desiccant solution inside the evaporator.
– The COPa is decreased and SMR is increased when the regeneration temperature is increased.
– The HDBAC system has been achieved a percentage of an energy savings in the range of 33–46%.

Remark/s: Strong desiccant solution is directly sprayed on the VCS evaporator inside the evaporator box

20. **Researcher/s:** D.Seenivasan, V.Selladurai, P.Senthil (2014-15) [23]
Study Type: Experimental/ Mathematical Model
LD Proportion and Type: Aqueous $CaCl_2$ solution with 30%, 35%, 40%, 45% concentration
LDAD System: Cross flow, structured packing with corrugated PVC sheets and non woven cloth, spray type adiabatic air dehumidifier.
Result/s:
– With the increase of air humidity ratio from 18g/kg to 24 g/kg, the average moisture condensation rate increases from 0.0016 kg/sec to 0.0020 kg/sec.
– The maximum average moisture condensation 0.0020 kg/s achieved at air humidity ratio 24 g/kg, desiccant temp. 30 ^{0}C, desiccant concentration 0.40 kg/kg, liquid to air flow rate 1.8 and desiccant flow rate 2.2 kg/s.
– In average, with the decreases in desiccant temperature, increase in air humidity, increase in desiccant concentration, decrease of liquid to airflow rate and with the increase desiccant flow rate the average moisture condensation rate from the air is maximum.
– The optimum values of input parameters for the given liquid desiccant air dehumidifier for maximum moisture condensation rate of 0.0035 kg/sec are:
  - Air humidity ratio (g/kg): 24.
  - Desiccant temperature (ºC): 25
  - Desiccant concentration (kg/ kg): 0.40
  - Liquid to Air flow rate ratio: 2.4
  - Desiccant flow rate (kg/s): 2.2

Remark/s: Mathematical model relating the effect of the influencing parameters on the moisture condensation rate has been developed using nonlinear regression analysis with the help of MINITAB software. MATLAB genetic algorithm (GA) has been employed to enhance the performance of the dehumidifier.

VII. CONCLUSION

The information and results given above can be concluded in general with regard to $CaCl_2$ liquid desiccant based air dehumidifier as follows:

- With decrease of temperature of $CaCl_2$ liquid desiccant the absorption capacity of it increases considerably but limited by the crystallization temperature.
- More $CaCl_2$ liquid desiccant concentration lowers vapour pressure of the liquid desiccant, which in turn give high potential for absorption of vapour from process inlet air.
- With higher air humidity ratio at inlet air, more moisture content can be absorbed and hence higher absorption effectiveness of air dehumidifier.
- As with higher moisture absorption rate, more heat content is released during absorption, which increases the temperature of desiccant and air, and hence affects the dehumidification process adversely.
- More $CaCl_2$ liquid desiccant flow rate surely gives higher absorption rate with appropriately more heat release during absorption.
- Moderate airflow velocity augment the dehumidification process very favorably but risk of carryover also goes up.
- Internal cooling of $CaCl_2$ liquid desiccant while absorbing moisture from the inlet process air gives very favorable condition to have maximum air dehumidification effectiveness and lower mass flow rate of the liquid desiccant followed by slightly complex and hence costly mechanism.

From the given performance evaluation of $CaCl_2$ liquid desiccant based air dehumidifier it can be seen that the performance of such air dehumidifier have been tested/experimented widely in terms of different boundary and operational parameters pertaining to air-liquid desiccant-cooling water and hence rigors research has been done and going on as well. It also depicts the acceptance of $CaCl_2$ liquid desiccant as a very economical and feasible medium for air conditioning in the category of liquid desiccant with the use of renewable energy sources, which makes it a very promising choice for further development for commercial success in years to come. Even though it has been used from quite a long years of span, the system could not been accepted on commercial basis; which gives very clear indication for commercial success design of the system in day to day utility for the coming years.

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