

Application of Liquid Desiccant Cooling Technology in Built Environment: A Review

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Abstract: Liquid-desiccant assisted dehumidification and cooling system has been proved to be an effective method to extract the moisture of air with relatively less energy consumption, especially compared with conventional vapor compression system. To date, the conventional dehumidification mode with desiccant solution has been improved or replaced by newly emerged energy-saving systems with better performance. This paper gives a detailed account of the general features of the various components used in desiccant dehumidification and cooling techniques; meanwhile, the effect of various operating parameters on system performance also highlighted. Moreover, a summary of the experimental and analytical studies to evaluate the system performance has been made. Some new hybrid systems that greatly expand the desiccant dehumidification technique in industrial and residential applications, as well as effectively promoting the single system's performance, are also reviewed through literature. Through a literature review, the feasibility of the desiccant cooling is proven by its comparison with conventional vapor compression system in terms of energy and cost savings are underscored. Finally, future study and application for liquid-desiccant dehumidification techniques are concluded.

Keywords: Cooling, dehumidification, liquid desiccants, regeneration, renewable energy.

1. INTRODUCTION

The role of the desiccant used in the dehumidifier is to remove water vapor from the conditioned air due to vapor pressure difference between the hot desiccant and the supply conditioned air. The desiccant can be categorized mainly into the two categories as solid adsorption and liquid absorbent desiccant materials. Several other types of solid materials are available in nature that can hold water vapor to the great extent to its weight, e.g., silica, polymers, zeolites, alumina and mixtures. Other commonly used liquid desiccant materials are calcium chloride, lithium chloride, lithium bromide, triethylene glycol and an equal mixture between calcium chloride and lithium chloride. These liquid desiccants have many thermo-physical properties, but their requirements cannot be fully described by any single desiccant. These requirements include low vapor pressure, low crystallization point, high density, low viscosity, low reactivation temperature, and economy [1]. The moist air is dehumidified by being brought into contact with strong liquid or solid desiccant, after this to provide sensible cooling to dehumidification process, traditional vapor compression, and vapor absorption, direct or indirect evaporative cooler units used. When the solution is weakened by absorption of moisture, it provided for the regeneration process that can loses its moisture content due to external thermal source. This called as reactivating the saturated desiccant material [2]. Thermal energy, at a temperature as low as 46–72°C required for reactivating of the liquid desiccant can efficiently obtained using a particular type of air or water solar collector or other primary heat renewable source [3]. The typical cycle of the desiccant is made up by three processes as shown in Figure 1 and Figure 2 depicts the fundamental deviation among traditionally used air conditioner and novel desiccant assisted dehumidification and cooling process [4]. The traditionally used vapor-compression cycle is now the foundation of the world air conditioning industry and will remain so for many years in conjunction with other hybrid cooling systems. The following problems are being addressed through a number of approaches including: (1) More efficient designs for household and commercial air conditioners, (2) More efficient buildings that require minimum or zero cooling, (3) The conversion

of power generation from fossil fuels to sustainable and renewable energy resources like as freely available solar energy, (4) The development of air conditioners that provide more efficient method of drying the moisture laden air, or latent cooling, more efficient ways, and (5) A wider implementation of energy storage technologies for different commercial and residential applications. Solutions do exist using only vapor-compression technology, but these solutions will increase the cost for producing thermal comfort by use of various air conditioning technologies. So, the desiccant assisted dehumidification and cooling system as a promising option to the traditionally used vapor-compression air conditioner may be better able to control the indoor thermal comfort while meeting the new economic, environmental, and performance requirements.

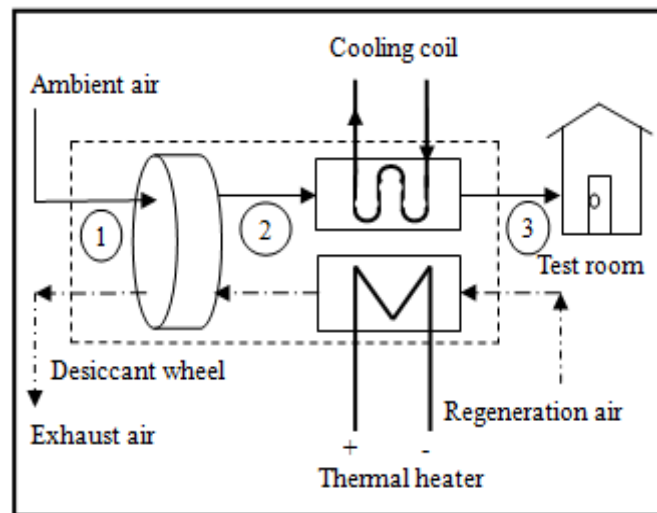


Figure1. Schematic Layout of Desiccant Integrated Dehumidification and Cooling Technique.

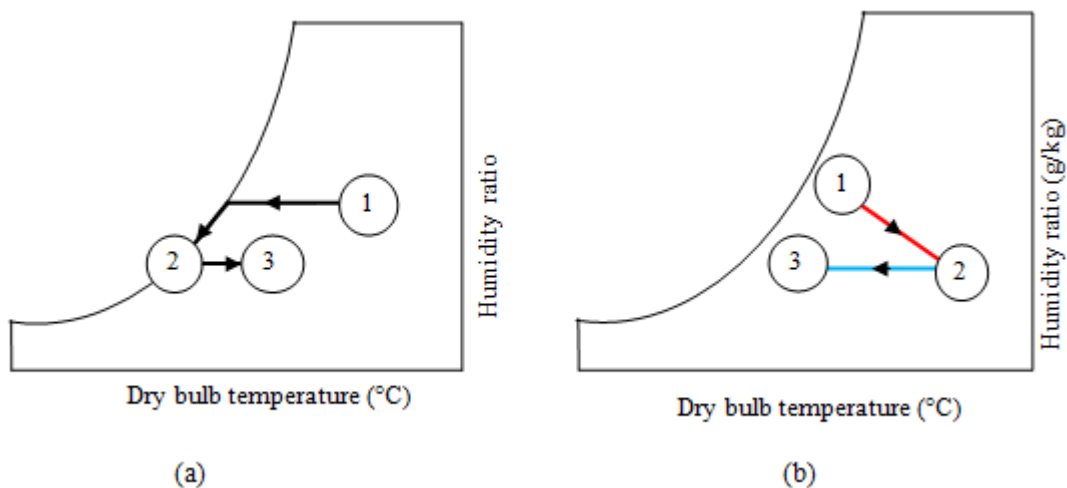


Figure2. Presentation (A) Conventional Cooling and (B) Desiccant Cooling on Psychrometric Chart.

2. WORKING PRINCIPLE OF THE LIQUID DESICCANT ASSISTED DEHUMIDIFICATION AND COOLING SYSTEM

The liquid desiccant cooling system consists of six major components namely an air dehumidifier, regenerator, two heat exchangers, and heater, cooler. The dehumidifier or absorber consists of a packed tower and operated in an adiabatic mode. While the regenerator is a device very similar to the dehumidifier, and so are the flow system and associated components. The regeneration heat required for desiccant reactivation is supplied by regenerator. The packing materials can be categorized as random packing materials and structured packing materials, the former are materials without regular geometric forms and placed randomly in the packing tower. While the opposite structured packing materials which have fixed geometric form. Pall ring, rosette ring, ladder ring etc. are among the widely used random packing materials in gas-liquid contacting industrial equipments, such as cooling

towers. The schematic layout of liquid-desiccant system is shown in Figure 3. The conditioner (or absorber) is the component that cools and dries the process air. As shown in this figure, the conditioner is a bed of structured contact media, similar to the corrugated fill that might be used in a cooling tower. Liquid desiccant is first cooled in a heat exchanger and then sprayed onto the contact media. The desiccant flow rate must be sufficiently high to ensure complete wetting of the media, meaning it should be about 4-6 gpm per square foot of face area. The process air is then cooled and dried as it comes in contact with the desiccant-wetted surfaces of the contact media. The absorption heat is released as the desiccant absorbs water from the air, but the high flow rate of the desiccant limits its temperature rise to a few degrees. The regenerator removes the water vapor absorbed by the desiccant during conditioning the room process air. The desiccant is reactivated by first heating it to raise its equilibrium vapor pressure. The hot desiccant, typically between 50-80°C temperature, is sprayed over a bed of random fill. Flooding rates are again sufficiently high to ensure complete wetting of the media. The hot desiccant desorbs water to the air that flows through the bed. This moisture laden air is typically exhausted to ambient. Both the regenerator and conditioner require droplet filters (also referred to as mist eliminators) to ensure that the desiccant is not entrained in either the supply air to the building or the exhaust from the regenerator. Droplet formation is fundamental to both the spray distributor and the highly flooded beds of contact media used in industrial equipment. Droplet filters can suppress desiccant carryover to parts per billion of airflow, but these filters do increase air-side pressure drops and require maintenance. An interchange heat exchanger (IHX) can be used to preheat the weak desiccant that flows to the regenerator using the hot, concentrated desiccant that leaves the regenerator. The IHX reduces both the thermal energy use of the regenerator and the cooling requirements of the conditioner. The corrosion effects on the operating components of the system should also be taken into account, the normal anti-corrosion methods adding additives to the liquid desiccant or choosing parts made of synthetic plastic for the system, which can simultaneously lower cost compared with metal parts.

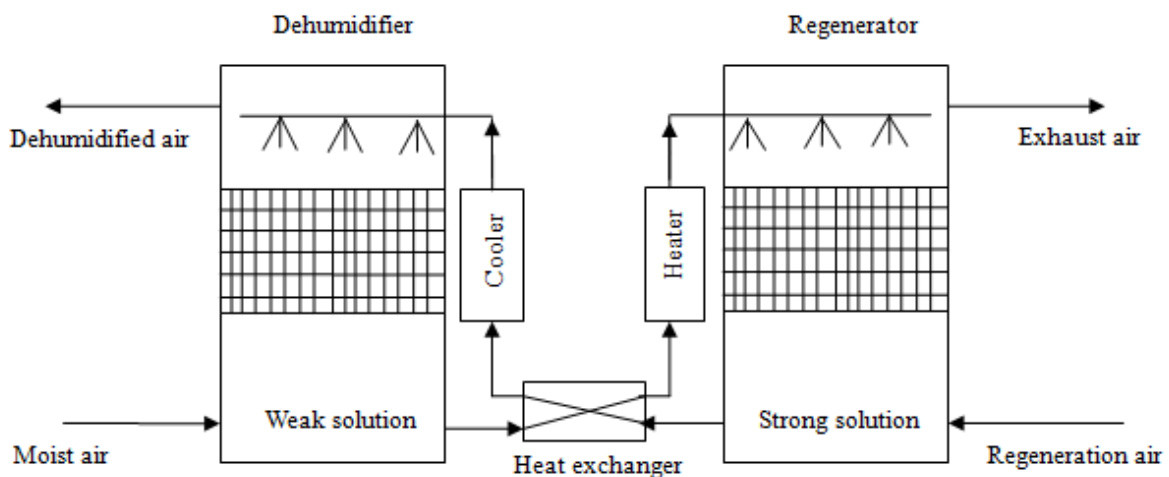


Figure3. Schematic Layout of Desiccant Assisted Dehumidification and Cooling System.

2.1. Literature Survey on Liquid Desiccant Assisted Dehumidification and Cooling Technique

Desiccants absorb moisture because of the difference in vapor pressure between the air and the surface of the desiccant solution. Dehumidification process starts when the vapor pressure of the surface of the desiccant is less than that of air and continues until the desiccant reaches equilibrium with air [5]. Many investigators have conducted studies earlier on liquid desiccant dehumidification systems. Scalabrin and Scaltriti [6] performed many experiments over internally cooled dehumidifier and heated regenerator to simulate an open process of summer air conditioning. Experimental study was also investigated by [7,8] to describe the mass transfer performance of a cross-flow dehumidifier and regenerator in terms of enthalpy efficiency and moisture efficiency and moisture removal rate and regenerator effectiveness, respectively. The obtained results show that the impact of air and desiccant inlet parameters on the dehumidifier and regenerator performance. Jain et al. [8] conducted experimental study on a liquid desiccant system had a falling film tubular absorber and a falling film plate regenerator. Mohammad et al. [9] proposed an artificial neural network (ANN) model for predicting the performance of a liquid desiccant dehumidifier in terms of the water condensation rate

and dehumidifier effectiveness. MATLAB code was designed to study feed forward back propagation. The results show that the maximum percentage difference between the ANN and experimental value for water condensation rate and dehumidifier effectiveness were 8.23% and 9.75%, respectively. Youtong and Hongxing [10] suggested an innovative configuration of an open cycle liquid desiccant system. The system uses the counter flow dehumidifier type and solar collector to regenerate the dilute solution. Two loops in the system: Liquid desiccant dehumidification loop and air dehumidification loop, also the system had two solution tanks connect to the liquid desiccant loop, the first for strong solution and the other for weak solution. Kumar [11] proposed new cycles to improve the COP and carried out experiments to study the impact of various factors on the performance of regenerator and dehumidifier. Peng and Zhang [12] simulated the heat and mass transfer processes in a solar liquid desiccant regenerator system. The results of simulation show that the increment of solution outlet concentration, regeneration efficiency, and storage capacity increase 72%, 46.5%, and 47%, respectively as effective solution proportion falls from 100% to 61%. Xiong et al. [13] investigated that the COP of the system increased from 0.26 to 0.74 when used a novel two-stage liquid desiccant dehumidification. Some produced chilled water [14–18] to cool the process air, so the reheat of the process air may be needed for the precise control of room air conditions. Jones [19] designed and tested low-flow liquid desiccant air handling system; a natural gas boiler uses to supply the heat and a cooling tower for heat rejection. COP of the system varied between 0.57 and 4.46. Martinez [20] suggested innovative idea to reduce the corrosion problem with use of organic absorbents instead of tri-ethylene glycol (TEG). In Taiwan [21–23] carried out a parametric study on a 9 m long solar C/R and investigated that the double-glazed forced convection well suitable in humid climates. These systems have several advantages over solid desiccants, including lower pressure drop of air across the desiccant material, suitability for dust removal by filtration, ease of manipulation and greater mobility. Kumar et al. [24] simulated, analyzed and modified the performance of standalone liquid desiccant system [25]. The main components of the system were absorber and regenerator type falling film; liquid desiccant falls under gravity in the form of a thin film on the side surface of the tubes from the top of absorber/regenerator. Two ways to modify the cycle, the first, by adding one absorber in parallel with the first absorber to reduce the load on it, the COP increase from 0.26 to 0.42 and the second modify is by adding a third absorber, the COP increase to 0.56. Li et al. [26] proposed a new regeneration method to regenerate the solution in the liquid desiccant system. The regeneration system is named photovoltaic-electro dialysis (PV-ED); a membrane is employed to regenerate the liquid desiccant in an electro dialysis, while the solar photovoltaic generator is adopted to supply electric power for this process. The new regeneration method achieves good stability with the immunity against the adverse impact from the outside high humidity; its performance is much higher than that of the thermal regeneration manner while putting aside the low efficiency of the photovoltaic system. Audah et al. [27] studied the feasibility of using a solar-powered liquid desiccant system, which used calcium chloride as liquid desiccant, parabolic solar concentrators as a heat source for regenerating the liquid desiccant. The liquid desiccant model predicted the amount of condensate obtained from the humid air leaving the regenerator bed when directed through a coil submerged in cold sea water. The optimal regeneration temperature increases with decreased heat sink temperature with values of 50.2°C and 52.4°C corresponding to sink temperatures of 19.4°C and 16.5°C. Jain et al. [28] used a liquid desiccant system had a double channeled exchanger for air to liquid desiccant heat and mass transfer; this way provides a large area of heat and mass transfer between the air and solution. The performance of the system was presented in terms of moisture removal rates and efficiency of dehumidifier/regenerator. Most of the physical parameters are measured against a suitable reference point directly. As reported in [29], the parallel flow channel provides better dehumidification and cooling processes of the air than counter flow configuration for a wide range of pertinent parameters. A liquid desiccant system using Li-Br for the process of absorption and dehumidification simulated by Ahmed et al. [30] with a hybrid open-cycle vapor absorption. Grossman [31] developed an open-cycle absorption chiller and desiccant system for use with low temperature heat sources such as a flat plate collector. The system consists of numbers major components, an indirect contact evaporative cooler, an air dehumidifier, two air to air heat exchanger and solution to solution heat exchanger. Artificial neural network proposed by Gandhidasan and Mohandes [32] to simulate the relationship between the inlet and outlet parameters of the dehumidifier in the liquid desiccant system. The results show that the dehumidification process can be alternatively modeled using artificial neural network with a reasonable degree of accuracy. Babakhani et al. [33] developed an analytical solution of the coupled heat and mass transfer process in a cross-

flow liquid-desiccant dehumidifier/regenerator. The results of the analytical solution show that air flow rate, air inlet humidity, desiccant inlet temperature, and desiccant inlet concentration have more influence on the moisture removal rate in the cross-flow dehumidifier, while desiccant flow rate, desiccant inlet temperature, desiccant inlet concentration, and air inlet humidity have more effect on the moisture removal rate in the regenerator. Lowernstein [34] studied mixtures of lithium chloride and calcium chloride as a lower-cost alternative to lithium chloride. The cost for calcium chloride is approximately one-twentieth that of the lithium salt. Mohamad et al. [35] reviewed the use of the alternatives for high latent air conditioners based on a conventional vapor-compression cycle. These advanced air conditioners typically add a heat and/or mass exchanger in the airstream to lower the sensible heat ratio (SHR) of the cooling process. These modified vapor-compression air conditioners have lower energy efficiency ratios (EER) than conventional units because of the additional air-side pressure drops across the added heat/mass exchangers. Table 1 shows below the summary of important work carried out previously in the field of desiccant cooling.

Table1. Summary sheet of literature survey on liquid desiccant assisted dehumidification and cooling

Author	System		Performance (COP)
	Description	Desiccant type	
Sethi and Sharma [36]	Analytical	CaCl ₂	0.34
Goshayshi et al. [37]	Experimental	CaCl ₂	0.21
Maheshwari et al. [38]	Simulation	Li-Br	0.74-1.19
Heidarinejad et al. [39]	Experimental	LiCl	0.2-1.3
Wu et al. [40]	Simulation	Li-Br	1.67
Dessouky [41]	Experimental	Water	0.58
Stoitchkov and Dimitrov [42]	Simulation	LiCl	0.29

2.2. Effect of Key Variables on The Performance of the Liquid Desiccant Cooling System

Flooding rates in packed-bed conditioners must be high, both to ensure complete wetting of the packing and to prevent heating of the desiccant. Although the first objective—complete wetting—might be realized at low flow rates by adding surfactants to the desiccant or treating the surface of the packing to increase its surface energy, the second—keep the desiccant cool—will always require a high flooding rate. Figure 4 [43] shows the temperature rise that occurs when a 43.2% solution of lithium chloride initially at 29.42°C adiabatically absorbs water vapor. If the quantity of absorbed water decreases the desiccant’s concentration to 42% and the desiccant is not cooled, the temperature of the desiccant will increase to 54.45°C. Whereas, initially the desiccant has an equilibrium dew point of 11.21°C, the 42.12% solution at the higher temperature has an equilibrium dew point of 36.12°C—a value much too high to be useful. If the more dilute desiccant is cooled to 29.47°C, its equilibrium dew point would be 12.17°C, and the desiccant could continue to dehumidify air.

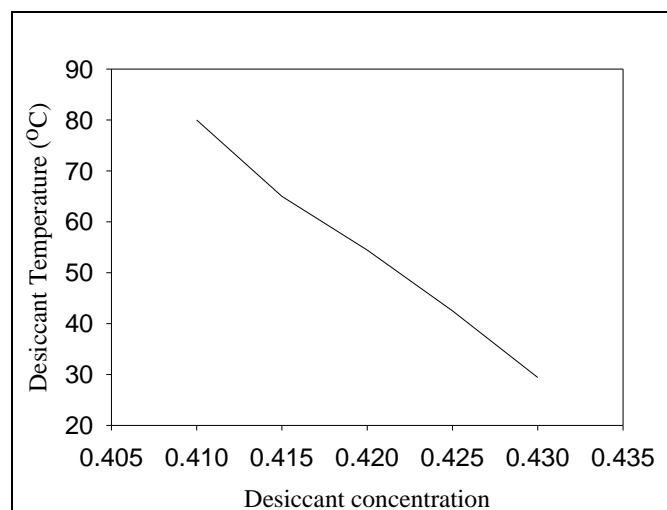


Figure4. Influence of desiccant concentration on temperature rise during adiabatic desorption process.

The improvement in COP produced by higher temperatures in scavenging-air regenerators results from the exponential dependence of the desiccant’s equilibrium water vapor pressure as shown in Figure 5. The hot desiccant that flows down the contact surfaces loses energy through both heat and

mass exchange with the air. The convective heat exchange is a parasitic loss that cools the desiccant without increasing its concentration. Since the driving potential for mass exchange—the desiccant’s equilibrium vapor pressure—increases exponentially with its temperature, but the driving potential for heat exchange increases linearly, a greater fraction of the input thermal energy will produce useful mass exchange when the regenerator operates at higher temperatures. The COP of a scavenging-air regenerator can be increased by preheating the air through heat exchange with the hot exhaust. In laboratory tests, Slayzak [44] reported that an internally heated regenerator operating at 93.34°C and processing 40% lithium chloride has a COP of 0.723 without heat recovery and 0.832 with heat recovery by a 70.2% effective heat exchanger.

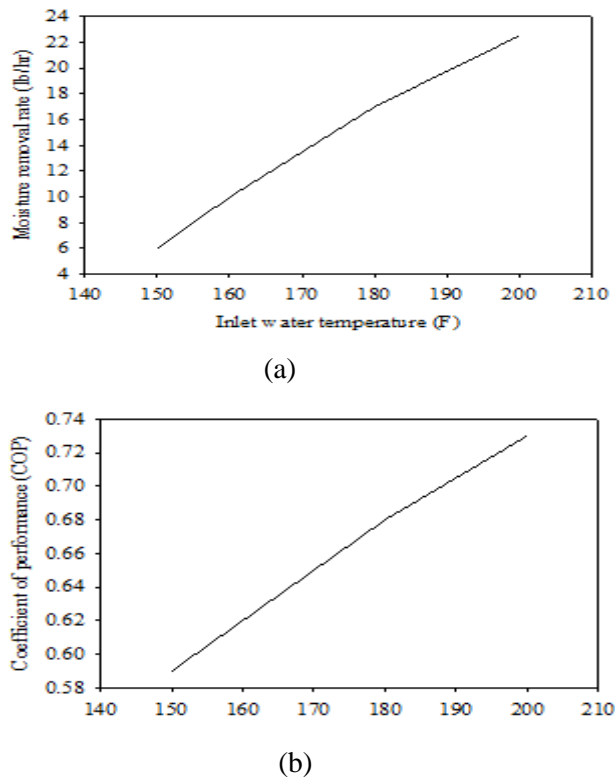


Figure 5. Influence of rise in regenerator water temperature at inlet on (a) moisture removal rate and (b) coefficient of performance of the liquid desiccant cooling system.

A packing material is a medium for liquid desiccant to interact with the process air stream to extract water vapor. A packing material must be inert to liquid desiccants. Packing materials and their configuration significantly affect the performance of dehumidification unit of the desiccant cooling system. They are broadly classified as regular/ structured packing and random packing based on their configuration. Regular packing ameliorates the performance of the dehumidifier by providing low-pressure drop for the air stream and is easy to install as compared with random packing. It also lowers the liquid desiccant resistance in the dehumidification unit. On the other hand, random packing material cannot adjust to the variation in liquid desiccant flows and results in uneven distribution of the desiccant solution over the surface of the packing material, which diminishes the performance of the dehumidification system. However, regular packing is costlier than random packing. Some common examples of random packing material include ceramic, plastic, polypropylene pall whereas structured packing material are either gauze type or sheet type. Structured packing materials are generally made of stainless steel-corrugated orifice plate, celdek, etc. Table 2 shows a summary of observations from different investigators.

Table 2. Influence of different types of packing materials used in absorber on system performance

Author	Type of packing material	Effect
Das and Jain [45]		
Ahmed et al. [46]	PVDF membrane	Lowers carry over
Bassuoni [47]	Silica gel	High dehumidification capacity
Kumar and Asati [48]	Structured packing	Higher effectiveness
	Random packing	Uneven distribution of desiccant

2.3. Comparison of Liquid Desiccant with Traditional Vapor Compression Cooling

Water vapor content or moisture of conditioned air can be controlled either by condensing the water vapour or by using suitable absorbents as used in liquid desiccant cooling systems. While conventional air conditioners simultaneously cool and dehumidify the air, a desiccant system first only dehumidifies it and later cools the same. Moreover, a desiccant system can be used in combination with evaporative cooling system to maintain the temperature and moisture of conditioned room air. Previously, the desiccant cooling systems were used for industrial and agricultural sector like textile mills, post-harvest crop storage units for humidity control and drying [49]. However, energy crisis and necessity to develop more eco-friendly systems have led to the introduction of desiccant cooling systems as an effective method to control humidity. Table 3 [50-51] provides a brief summary of major differences between the liquid desiccant systems and vapor compression based conventional air conditioners.

Table3. Comparison between traditional coolers and liquid desiccant assisted innovative cooling

Parameter	Conventional air conditioner	Liquid desiccant cooling
Operating cost	High	Saves 41-48%
Indoor air quality	Average	High
Effect on environment	Harmful	Eco-friendly
Energy source	Electricity	Low grade heat like waste heat or renewable solar energy
Moisture removal capacity	Average	High

2.4. Future Scope in Various Applications of Liquid Desiccant Assisted Dehumidification and Cooling

Liquid-desiccant dehumidification advanced cooling technology has made great strides in the past few decades, and some are commercialized and successfully used in many applications to satisfy industrial dehumidification and residential thermal cooling needs of the society. Theoretical models about desiccant dehumidification have been established and insightful analysis has been performed [52-55]. However, it is still uncertain about the exact process of mass and heat transfer, such as the absorption heat distribution between desiccant solution film and process air, wetting ratio of the desiccant solution over the packing sheets in dehumidifier, etc. Although liquid-desiccant dehumidification systems can easily realize the separate handling of temperature and humidity of the moist air to be cooled and processed, but it has the potential limitation about its utility in mild ambient, which hinder its widespread applications, besides, its continuous operation and performance is greatly affected by the changeable environmental conditions at various geographical locations on earth, since the performance of solar collector is mainly judged partly by the ambient air conditions and solar radiations received. Therefore, the system performance is deviated much according to the existing ambient conditions as compared with that of vapor compression based conventional air conditioning units. The emergence of hybrid systems will partly reduces the system's instability, besides, hybrid system's capacity for handling the sensible cooling of the process air far outweigh that of conventional sensible type coolers, which is commonly employed by the traditional liquid-desiccant dehumidification and cooling systems in various industrial and residential applications. Furthermore, the evaporation cooler's cooling efficiency is limited by the geometrical environmental existing situations [56-60]. Above all, hybrid systems should be placed emphasis on to wide spread popularity of desiccant dehumidification assisted cooling techniques for space comfort monitoring. Also, further analytical and experimental research and innovations should be made to still further depth so that the understanding of mass and heat transfer occurring within the dehumidifier can ameliorate further the system's overall performance for its better suitability.

3. CONCLUSION

One of the important aspects over the use of liquid desiccant dehumidification and cooling system in building air conditioning is that it can efficiently eliminate the major content of the latent part that consists of mainly the moisture heat of the processed air and regenerate it with low temperature using freely available energy such as solar and waste energy. This review has revealed that liquid-desiccant assisted dehumidification and cooling technique is an economic and environmental friendly cooling

technology that can be improved further by coupling it judiciously with the other traditional air conditioning techniques. There are many innovations and improvement that can demand several design optimizations in liquid desiccant assisted cooling systems like as carry-over of liquid desiccant at high flow rates, reverse dehumidification at low air humidity ratios and corrosion of the dehumidification unit and storage tank in case of any leakages. Many investigators have suggested that the problem of carry-over can be by using micro-porous membrane, which would only allow the air to pass and not the liquid desiccant. However, such membrane also increases the mass transfer resistance. The present summary about the liquid desiccant cooling show that the liquid desiccant systems have been successful in efficiently eliminating the latent and sensible load to a considerable extent. Thus, replacing conventional vapor compression with hybrid desiccant systems would increase the energy savings potential of this innovative cooling technology considerably in present HVAC market.

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