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# A Review on Liquid Desiccant Powered Hybrid Air Conditioning for Indoor Thermal Comfort in Building

**D.B. Jani**

*Department of Mechanical Engineering, GEC, Dahod, Gujarat Technological University, GTU, India*

***Corresponding Author:** D.B. Jani, Department of Mechanical Engineering, GEC, Dahod, Gujarat Technological University, GTU, India, Email: dbjani@rediffmail.com*

## ABSTRACT

*In hot and humid climates, the liquid desiccant dehumidification assisted air conditioning cooling technology was proposed as an option to conventionally used vapor compression based traditional HVAC devices used for building dehumidification and cooling. Desiccant cooling can replace VCR systems as they handle the sensible and latent load separately; in absence of CFC based refrigerants it is environment friendly and reduce the high grade electrical energy consumption by use of renewable or waste heat. Desiccant cooling has been considered as an effective technique to control the moisture content in the supply air in building comfort cooling. Various components of the liquid desiccant cooling have been discussed in detail. The present article describes recent research and development activities done in the field of desiccant cooling over the period of time.*

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

## INTRODUCTION

The role of the desiccant used in the dehumidifier is to absorb the moisture from the supply room air due to vapor pressure difference between hot desiccant and cold room air. The desiccant can be classified as both solid and liquid desiccant materials. Several types of solid materials can hold off water vapor, e.g., silica, polymers, zeolites, alumina and mixtures. Other available liquid desiccants are calcium chloride, lithium chloride, lithium bromide, tri-ethylene glycol, and an equal mixture between calcium chloride and lithium chloride. These liquid desiccants have common general 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 sends direct to regeneration process to release the moisture by using an external heat resources. This is called regenerating the saturated desiccant [2]. Thermal energy, at a temperature as low as 45–70°C required for reactivating of the liquid desiccant can efficiently obtained using a solar collector [3]. The typical cycle of the desiccant is made up by three processes as shown in Figure 1and Figure 2 illustrates the difference between conventional air conditioner and desiccant assisted cooling process [4]. The vapor-compression cycle is now the foundation of the HVAC industry and will remain so for many years. The following problems are being addressed through a number of approaches including: (1) more efficient designs for air conditioners, (2) more efficient buildings that require less cooling, (3) the conversion of power generation from fossil fuels to sustainable resources, (4) the development of air conditioners that provide more dehumidification, or latent cooling, more efficiently, and (5) a wider implementation of energy storage technologies. Solutions do exist using only vapor-compression technology, but these solutions will increase the cost for air conditioning. Alternatives to the vapor-compression air conditioner may be better able to meet the growing demand while meeting the new economic, environmental, and performance requirements.

## NOMENCLATURE

| | |
|---|---|
| *A* | area ($m^2$) |
| *ANN* | artificial neural network |
| *CFC* | chlorofluorocarbon |
| *COP* | coefficient of performance |

| | |
|---|---|
| *EER* | energy efficiency ratio |
| *HVAC* | heating, ventilation and air conditioning |
| *IHX* | interchange heat exchanger |
| *PVDF* | Polyvinylidene difluoride |
| *PVED* | photovoltaic-electro dialysis |
| *SHR* | sensible heat ratio |
| *TEG* | tri-ethylene glycol |
| *VCR* | vapor compression refrigeration |

**Greek Symbols**

| | |
|---|---|
| $\eta$ | Efficiency |
| $\rho$ | Density (kg/m$^3$) |

**Subscripts**

| | |
|---|---|
| *1* | initial conditions |
| *2* | final conditions |

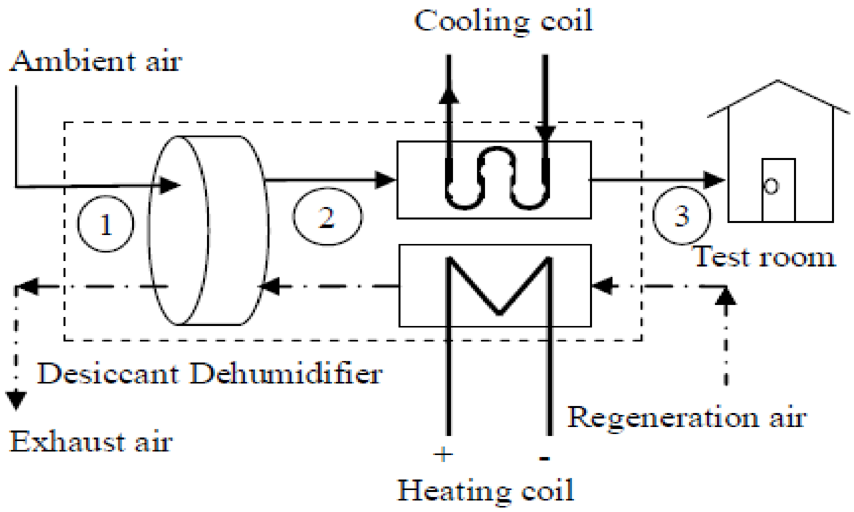


**Figure1.** *Working principle of desiccant cooling*

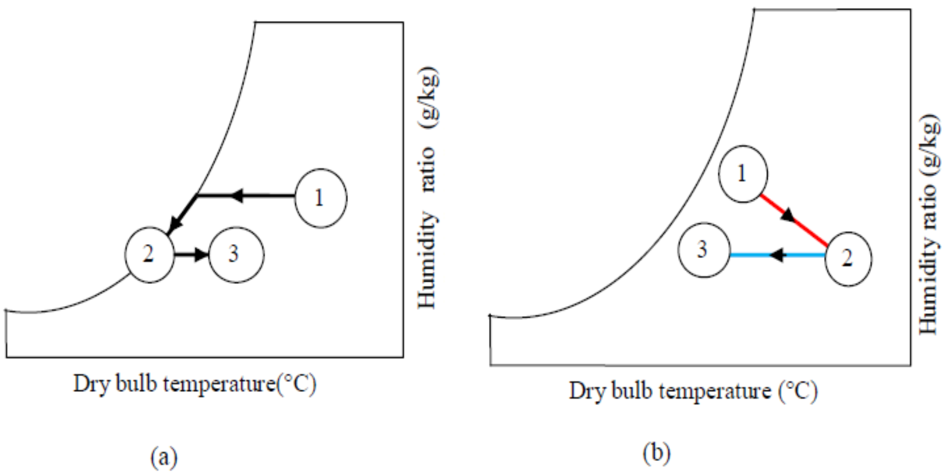


**Figure2.** *Difference between conventional cooling (a) and desiccant cooling (b)*

## WORKING OF LIQUID DESICCANT COOLING SYSTEM

Working 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 cooled and dried as it comes in contact with the desiccant-wetted surfaces of the contact media. 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 that the desiccant has absorbed in the conditioner. 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.

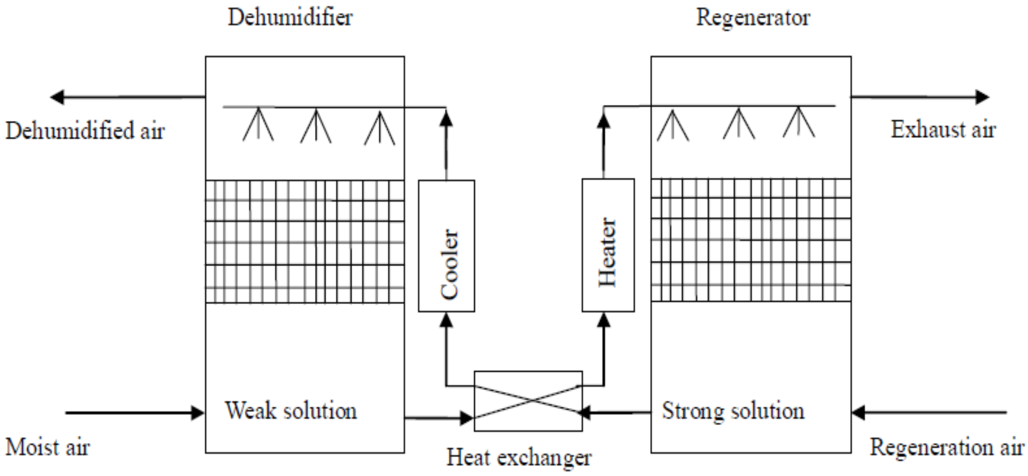


**Figure3.** *Construction and working of liquid desiccant dehumidifier*

## SURVEY OF IMPORTANT LITERATURES

Desiccants absorb moisture because of the difference in vapor pressure between the air and the surface of the desiccant solution. Dehumidification process is 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 crow-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 sys-tem 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°Cand 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 sys-tem 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. Lowenstein [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 of literature survey on desiccant 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 |

## Effect of Operating Parameters on Performance of 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.

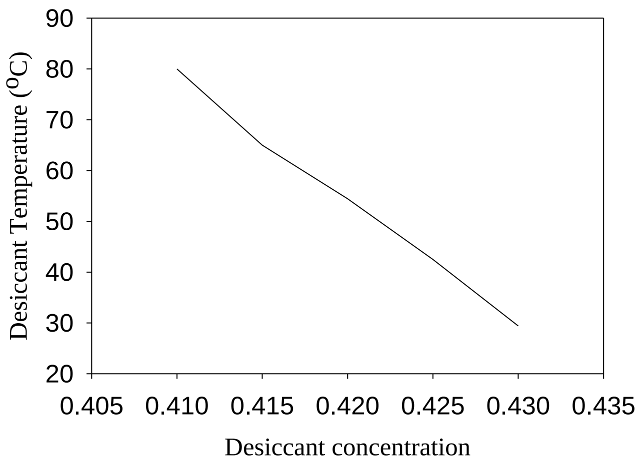


**Figure4.** *Effect of desiccant concentration on temperature rise during adiabatic desorption process.*

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.

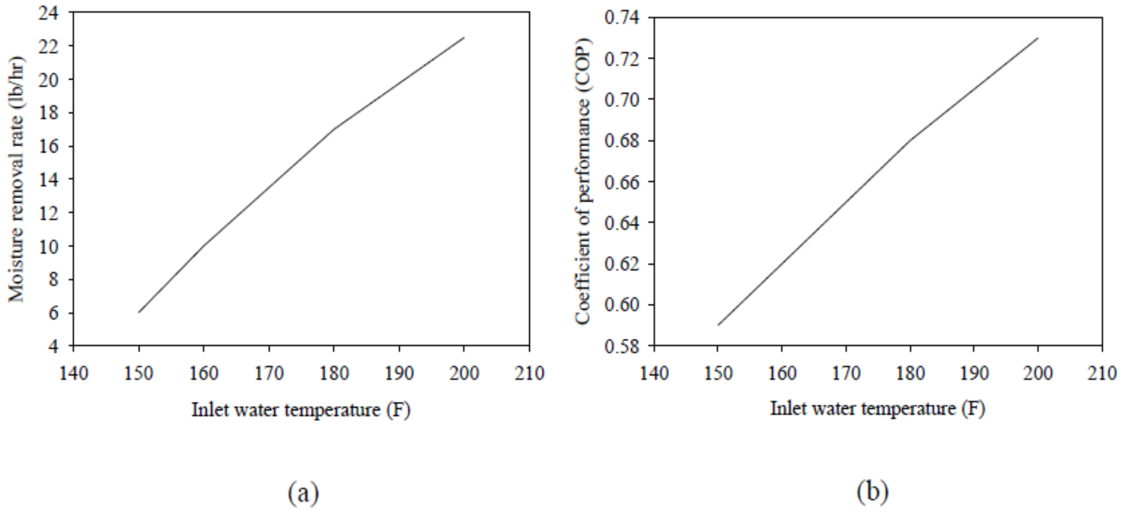


**Figure5.** *Moisture removal rate (a) and coefficient of performance (b) at different inlet water temperature in regenerator.*

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.

**Table2.** *Effect of various packing materials used in absorber*

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

## Comparison of Liquid Desiccant with Vapor Compression Based Conventional 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 conventional air conditioners and liquid desiccant 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 |

## CONCLUSIONS

One of the important aspects over the use of liquid desiccant dehumidification and cooling system in building air conditioning is that it can remove the major content of the latent heat of the processed air and regenerate it with low temperature using freely available energy such as solar and waste energy. This review has demonstrated that liquid-desiccant dehumidification is a simple technology that can be improved by combining the other conventionally used cooling technologies. There are many concerns that require several design optimizations in liquid desiccant 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 review of liquid desiccant cooling show that the liquid desiccant systems have been successful in reducing the latent and sensible load to a considerable extent. Thus, replacing conventional vapor compression with hybrid desiccant systems would increase the energy savings considerably.

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## BIOGRAPHICAL INFORMATION

**Dr. (Prof.) D.B. Jani** received Ph.D. in Thermal Science (Mechanical Engineering) from Indian Institute of Technology (IIT) Roorkee. Currently he is recognized Ph.D. Supervisor at Gujarat Technological University (GTU). Published more than 122 Research Articles in reputed International Conferences and Journals. Presently, he is an Associate Professor at GEC, Dahod, affiliated to Gujarat Technological University, GTU, Ahmedabad (Education Department, State of Gujarat, India). His area of research is Desiccant cooling, ANN, TRNSYS, and Energy.

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