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Review on Performance Analysis of Desiccant-Assisted Hybrid Cooling Systems

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ABSTRACT

Due to the growing expense of fossil fuels and other environmental issues, it is crucial to reduce the energy cost of built environment cooling systems without sacrificing indoor air quality and comfort levels. One option in this area is solid desiccant dehumidification-assisted cooling systems, which employ alternative energy sources like solar and biomass and are also environmentally beneficial by the minimal requirement of refrigerants. The present review discusses the performance analysis of different solid desiccants readily accessible on the market and their composites. Better moisture absorption and a lower regeneration temperature are qualities of a better desiccant. The review also discusses the various solid desiccant dehumidifier designs, their benefits, and their disadvantages. Solid desiccant dehumidifiers now come in various combinations, considerably enhancing system performance. The exergy efficiency of desiccant-integrated evaporative cooling is up to 21.5%, comparable with another HVAC system. A summary of the performance parameters has also been created to assess system performance further. This study will benefit innovation and advancement in solid desiccant materials in the air conditioning market.

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1. Introduction

Residential and commercial buildings need much primary energy for upkeep and to support the activities of their occupants since indoor environments are primarily utilized for human activities. The demand for energy used in producing thermally controlled environments is anticipated to rise due to rising standards of living and population growth, both of which directly impact energy use. It is anticipated that between 2022 and 2038, the amount of electrical energy used for interior environments will almost double. The building's cooling load is divided into sensible and latent, respectively. Alternative approaches are needed to maintain thermal comfort levels and improve indoor air quality while reducing energy usage and greenhouse gas emissions. Through the use of specific alternative energy resources, such as solar, biomass, etc., these alternative systems significantly lower the building's energy usage. Desiccant cooling, absorption cooling, and jet cooling are a few different thermal cooling technologies that directly use thermal energy [1–3]. These systems may successfully utilize solar energy due to variations in cooling demand that are in phase with the sun's rays throughout the day. There are several ways to transform solar energy for air conditioning. The cooling effect of the thermal cooling system is achieved by using thermal energy [4–7].

A significant worldwide environmental problem is emerging due to the rapid depletion of traditional energy supplies and the rising demand for human comfort levels brought on by the world population. Energy, environmental, and technological challenges are intertwined and must be addressed concurrently for a clean and better world. Burning traditional energy sources releases many greenhouse gases into the atmosphere [8–13]. The world's emerging nations' rapid population growth and economic progress are the leading causes of the annual rise in carbon dioxide emissions. Using heating and cooling equipment contributes significantly to the emission of these gases, which contributes to ozone layer depletion and other environmental problems. All of these contribute to a rise in the earth's temperature, leading to many climatic and meteorological disturbances, including cyclones and floods. A rise in greenhouse gases brought on by human activity impacts people's health and the viability of civilization.

To control interior air temperature and relative humidity for human comfort. Standard compressor-based air conditioners are good at controlling the apparent load of a building. However, they are less successful at Liquid desiccant materials effectively handling the latent loads of the same structure. These systems waste significant energy by overcooling the air below its dew point to remove moisture via condensation, then reheating the air to the desired supply temperature [14–19]. Second, because of surface moisture caused by the overcooling process, mold and bacteria may develop, hurting indoor air quality and resulting in health problems. A substitute is needed to eliminate this energy loss caused by overcooling and reheating. In hot and humid conditions, the latent load is more prevalent, necessitating air conditioning systems to efficiently manage the latent loads. Solid desiccant cooling systems are a workable and affordable solution for providing human comfort in hot and humid settings.

During the regeneration and absorption phases, it absorbs and desorbs moisture from and into the air, respectively. Heat and mass are transferred simultaneously in the solid desiccant cooling system. The mass (moisture) transfer from the humid air to the solid desiccant surface regulates the latent load [20–24].

Rotary desiccant dehumidifiers for air conditioning are considered one of the most promising air conditioners for regions suffering from high humidity and temperatures. The harmful effect of incorporating the rotary desiccant wheel with air conditioning systems is the heat generated by the adsorption effect, which causes increases in the air temperatures within the rest components of the air conditioning systems. To solve this problem, an innovative novelty configuration of the desiccant dehumidifier that contains multi-stages of silica-gel pads and heat exchangers for inter-cooling is required. This innovative novelty configuration of the desiccant dehumidifier increases the dehumidification capacity as well as cools the process air with cooling rates higher than the heat generated by the adsorption effect, which leads to a decrease in the sensible load and saves more and more in electrical energy as compared to the conventional cooling systems.

The size of the cooling system and the bulk of refrigerant fluid are significantly reduced due to the independent management of temperature and humidity. As a result of reduced emissions of greenhouse gases that damage the ozone layer, the system is also made more environmentally friendly and energy-efficient. Since desiccant materials have sanitizing properties, desiccant cooling systems may provide higher Indoor Air Quality (IAQ). The condensed water is created during condensation in traditional systems, which promotes the development of several fungi, viruses, and bacteria. These have a significant impact on human health and IAQ. The usage of desiccant devices prevents the production of condensed water. Desiccant technology is thus highly advised for applications needing the ongoing maintenance of stringent hygiene standards, such as pharmaceuticals and labs [25–29].

This paper aims to check the feasibility of EC systems and those combined with desiccant air-conditioning systems for comfort cooling in air-conditioning applications. These are well-known air-conditioning techniques, but the application could be more in the air conditioning sector. This paper aims at the novelty of AC system configurations for air conditioning applications.

2. Solid Desiccant Cooling

Fig. (**1**) illustrates a typical schematic configuration for a solid desiccant-assisted dehumidification and hybrid cooling system. According to the configuration, humidity is decreased when air moves through the desiccant wheel. The warm and dry air is further cooled after passing through the sensible air cooler, which further lowers the air temperature to the design conditions and is then supplied to the building. The return air is then heated in a heat exchanger.

They use solar or electric energy to reach the regeneration temperature. When the high-temperature returns and airflow pass through the solid desiccant wheel, the solid desiccant is then revived. The exhaust air is released onto the environment.

Desiccant dehumidifiers use changing vapor pressures to dry air continuously in a repeating cycle described by the simplified equilibrium diagram at left. The desiccant begins the cycle at point one. Its surface vapor pressure is low because it is dry and cool. As the desiccant picks up moisture from the surrounding air, the desiccant surface changes to the condition described by point two. Its vapor pressure is now equal to the surrounding air because the desiccant is moist and warm. At point two, the desiccant cannot collect more moisture because there is no pressure difference between the surface and the vapor in the air. Then the desiccant is removed from the moist air, heated, and placed into a different airstream. The desiccant surface vapor pressure is now very high — higher than the surrounding air — so moisture moves off the surface to the air to equalize the pressure differential. At point three, the desiccant is dry, but its vapor pressure is still too high since it is hot to collect moisture from the air. The desiccant is cooled to restore its low vapor pressure, returning it to point one in the diagram and completing the cycle to collect moisture once again [30–34].

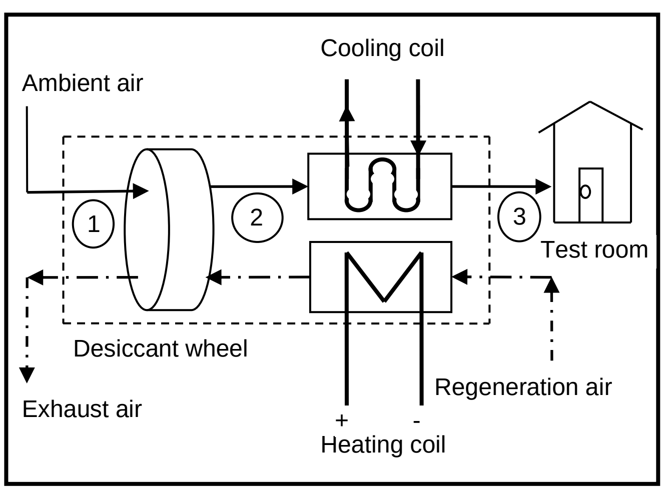

Figure 1: Schematic diagram of the solid desiccant integrated hybrid air-conditioning system.

In order to increase the regeneration efficiency of the system, the surface vapor pressure of the desiccant must be increased by preheating the dry air leaving the dehumidification unit. The difference in surface vapor pressure between the solid desiccant layer and humid air drives mass/moisture transfer. Similarly, pre-cooling entering air at the dehumidifier at the input is required to reduce its surface vapor pressure to increase the dehumidification process' efficiency. Between the two streams, heat exchangers (Fig. **2**) are used to efficiently pre-cool the air coming out and preheat the entering air in the dehumidification unit. An additional heater might be added to prevent system overload. This auxiliary heater may compromise the system's functioning due to excessive moisture in the rainy season [35–39].

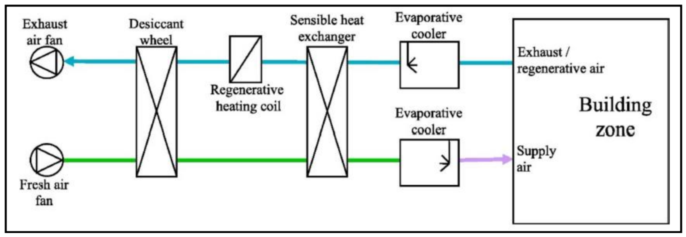

Figure 2: Use of sensible heat exchanger in hybrid cooling.

3. Liquid Desiccant Cooling

In a liquid desiccant cooling system, a liquid sorptive desiccant material or chemical, such as lithium chloride, is utilized to regulate the room's relative humidity from the room process air supply. The basic setup consists of static bed desiccant packing materials as the concentrated solution, which following cooling, flows into the absorber tower from room process air (Fig. **3**). Return air rises through the mattress, transferring moisture and heat into the liquid desiccant that is positioned in opposition to it. The liquid desiccant is injected from the bottom of the packed bed into the hot regenerator after combining a significant amount of condensed water extracted from moisture in the room process air. Before spraying over another full bed, the weak liquid desiccant solution is warmed using a reactivation heat source. The heated desiccant material removes moisture from the exhaust air from the regenerator column to refresh a concentrated liquid desiccant solution. After exchanging the appropriate heat with the weak solution from the chiller, the liquid desiccant solution is cooled. It then returns to the absorber to complete the cycle [40–43].

Designs usually include a heat-exchanging device intermediate between the desiccant flow from the regenerator and the absorber to reduce the amount of outdoor heating and cooling required. Liquid desiccant devices generally employ a salt solution's sorptive properties to dry the room's process air.

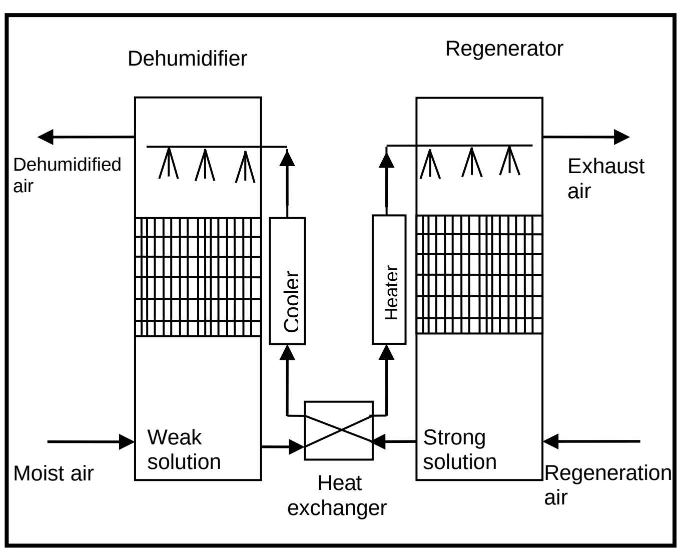

Figure 3: Schematic working of liquid desiccants.

When exposed to humid room air, which is often outside air, the solution pulls moisture from the high vapor pressure side to the lower vapor pressure side of the desiccant. The air adiabatically approaches the constant enthalpy line on the chart as it passes through the dehumidifier. The room's dry-bulb temperature may be lowered by introducing the air into it with a practical cooling coil [44–47].

4. Comparison between Solid and Liquid Desiccants

Desiccant cooling systems are categorised into liquid desiccant and solid desiccant. Zeolite, lithium chloride, lithium bromide, calcium chloride, silica gel, and alumina are commonly used solid desiccants. Before being pumped within a building, outside air is dried using the solid desiccant silica gel. Liquid desiccant is the component of desiccant systems that matters the most. Among all of the properties of the dehumidifier, the surface vapor pressure has the most significant impact on how much mass and heat are moved. Most liquid desiccants are non-flammable, odorless, non-toxic, and reasonably priced. Numerous solid-packed vertical beds, fluidized beds, inclined fluidized beds, rotating honeycombs, and fluidized beds all employ silica gel as desiccant dehumidifiers. The solid-packed bed can withstand substantial moisture levels, but the rotating honeycomb gets more constant humidity in process air. The two desiccant dehumidifiers have advantages and disadvantages [48–53].

Fig. (**4**) compares the pattern of the annual COP for liquid and solid desiccant systems based on the working hours of each system. The results show that the performance of the liquid desiccant cooling system is subpar compared to that of the solid desiccant cooling systems. It was also claimed that solid desiccant devices had the advantage of using less water and energy. However, according to numerous researchers in this field, the method's limited reliability and effectiveness within a confined set of parameters renders the prediction models inappropriate for various climatic conditions and circumstances [54, 55].

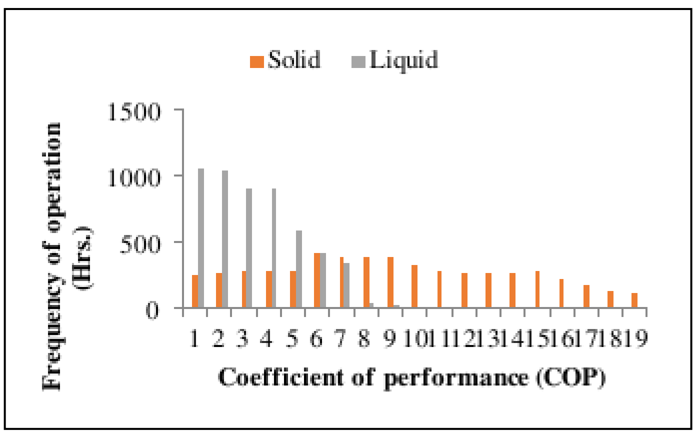

Figure 4: Operational differences among solid and liquid desiccants.

5. Composite Desiccant Materials

In recent applications, composite desiccant materials are the most often used in integrated desiccant dehumidification and cooling systems. In recent studies, among the numerous innovative desiccants, hygroscopic salt is impregnated into the pores of a porous desiccant substance to create them. Silica gels, mesoporous silicate, active carbon, natural rocks, and other conventional porous desiccant materials offer the benefits of stable properties and inexpensive cost. However, the drawback of limited adsorption capacity results in the enormous bulk of desiccant units. In contrast, hygroscopic salts (such as haloids, nitrates, sulfates, etc.) have a higher sorption capacity. However, they are less stable, particularly in environments with high humidity levels due to lyolysis (the appearance of wetting followed by that of a liquid solution, which frequently occurs after the formation of a solid crystalline hydrate). As a result, desiccant materials may be lost, and dehumidification efficiency may decline. These two kinds of materials may be traded off well with composite desiccant materials:

1). Physical adsorbent stability and strong hygroscopic salt sorption qualities may be maintained;

2). The deliquescence issue is significantly reduced because dissolved salt can be retained in the pores of its host matrix.

Some composite desiccant materials listed above are used for adsorption cooling also. Previous studies have shown that composite adsorbents improved both the amount of water absorbed and the COP (coefficient of performance), demonstrating the significant potential of composite adsorbents for adsorption cooling.

Due to these benefits, composite materials of various host matrices and confined salts have developed more recently [56–58].

The field of material science has advanced significantly in recent years. Several of the materials indicated above come close to meeting the specifications for integrated desiccant dehumidification and cooling systems in different commercial and household applications. For instance, the support of impregnated salts has increased the water adsorption capability of composite desiccant materials. Regeneration temperatures as low as 45 °C near ambient temperatures may be attained with the suitable host matrix and submerged salts, i.e., clay/chlorine salt composite materials. In addition, a good balance between regeneration and water sorption capacity may be achieved by carefully adjusting the textural features of nanoporous inorganic materials. With the advancement of material science and molecular modeling, a significant advancement in the practical use of adsorptive dehumidification is envisaged for polymeric desiccants, especially composite-type compounds and laminates. Despite these remarkable advancements, no material can completely meet all the criteria.

6. Performance Analysis

The performance evaluation of desiccant VCR integrated hybrid dehumidification, and cooling system depends on many factors such as changes in environmental conditions, air flow rates in process and reactivation sides respectively, pressure drop across dehumidifier, variations in human occupancies in the room and seasonal changes in an outdoor environment. Performances indices are moisture removal rate, cooling capacity, coefficient of overall system performance, etc.

The critical indicator for the performance evaluation of dehumidifiers is the moisture removal rate (MRR) and effectiveness (ε_{dw}) measured and calculated for considering the process and reactivation of air [56, 59–61]. The moisture removal rate or moisture transfer rate is generally given as

$$\text{MRR} = \dot{m}_{pa}(\omega_1 - \omega_2)$$

Where $\dot{m}_{pa}$ is the mass flow rate of process air at the desiccant wheel process air inlet, ω1 and ω2 are the humidity ratios of process air at the intake and exit of the desiccant wheel, respectively [62, 63]. The effectiveness of the desiccant wheel is calculated by evaluating the ratio of the change in possible humidity ratio of the air to the maximum possible change in humidity ratio of the process air side of the dehumidifier.

The following equation has denoted the effectiveness of the rotary desiccant dehumidifier.

$$\varepsilon_{dw} = \frac{\omega_1 - \omega_2}{\omega_1 - \omega_{2,ideal}}$$

The coefficient of performance of the system based on electrical supply energy to run the electrical motor energy input is calculated by knowing the ratio of the cooling capacity to the total electrical energy supply to the electric motor (E_{total}), as mentioned by

$$\text{COP} = \frac{Q_{cc}}{E_{total}}$$

In the above equation, Q_{cc} is the cooling capacity of the sensible cooling coil and is given as

$$Q_{cc} = \dot{m}_{pa}(h_1 - h_4)$$

Where $\dot{m}_{pa}$ is the mass flow rate of process air at the desiccant wheel intake side. While total electric energy consumption by all the above components can be summarised as E_{total}, the total electrical power is denoted as

$$E_{total} = E_{compressor} + E_{fan} + E_{heater} + E_{others}$$

Where personal power for running the compressor and fan used in the system were $E_{compressor}$ and E_{fan}, respectively, two fan processes and reactivation air circulation were used. The notation for the electric power utility for running the reactivation heater is E_{heater}. Power consumption for the other auxiliary equipment is denoted as E_{others}.

Fig. (**5**) compares electrical energy usage for desiccant cooling versus vapor compression-based traditional cooling. The hourly power usage of the integrated desiccant dehumidification cooling system and the traditional vapor compression cooling system are combined during the summer cooling season for the tropical hot and humid environment to give a more concrete comparison. A significant decrease in electrical energy consumption might be achieved by comparing the desiccant dehumidification and cooling system to the traditional vapor compression cooling system. The findings provide an intriguing insight into the huge energy savings potential of desiccant dehumidification and cooling systems in tropical and subtropical humid environments [64–66].

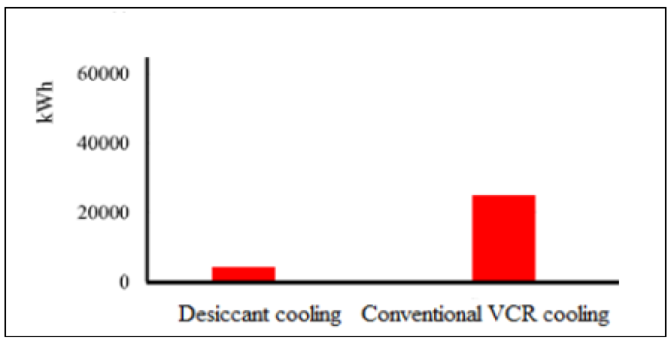

Figure 5: Desiccant versus conventional cooling in energy savings.

The construction industry's energy consumption and environmental effects depend heavily on space heating and cooling.

The total carbon dioxide emissions of the desiccant dehumidification and cooling system and the traditional vapor compression cooling system during the summer cooling season are illustrated in Fig. (**6**) to assess the carbon-saving potential. Each energy carrier's carbon emissions are comprised of on-site and off-site emissions. Significant carbon dioxide emissions will be preserved during the summer cooling season by using the desiccant

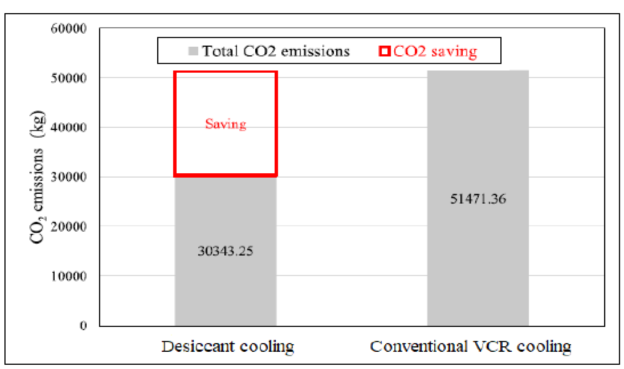

Figure 6: Desiccant versus conventional cooling carbon savings.

dehumidification and cooling system. These findings suggest that a desiccant dehumidification and cooling system might substantially lower the carbon dioxide emissions of space cooling in a hot, humid tropical or subtropical climate, offering a more environmentally friendly cooling solution [67–69].

Desiccant-integrated dehumidification and hybrid cooling systems may save much energy by reactivating the desiccant material used in the system's rotating dehumidifiers using waste heat from industrial operations, which increases the cost-effectiveness of the hybrid cooling system. Using renewable solar energy can reduce the peak electrical power demand from the traditional vapor compression air conditioning system during hot, sunny days. Future developments in the advanced kind of desiccant materials that regenerate at lower reactivation temperatures by using low-temperature waste will increase the contribution of desiccant cooling, which may improve comfort and result in energy and money savings.

The comparison of this system with other HVAC systems from an exergy point of view is given in Table **1**.

Table 1: Compares desiccant cooling with other HVAC systems from exergy efficiency criteria.

S. No.	Type of HVAC System	Overall Exergy Efficiency
1	Solid desiccant evaporative cooling system	21.5
2	Ground source heat pump system	9.88
3	Thermally driven Compression system	12
4	Vapor compression refrigeration system	14.8
5	Li-br absorption system	16

Desiccant regeneration heat from primary energy is the preferred option for reducing high-grade electrical energy usage. Since the desiccant dehumidification and cooling system may be used to lower overall energy requirements without maintaining a low temperature to remove moisture from the external air. The cooling demand profile and the simultaneous presence of intense solar radiation make renewable solar energy the most practical option. The sensible heat is retained, and the surrounding air is pre-cooled using an air-to-air heat recovery device.

The main challenges that desiccant-aided contemporary air conditioning systems must overcome to get wider acceptance in space cooling include a further increase in energy utilization rate, decrease in cost and size, competitive design, and manufacturing [70–74].

7. Conclusion

The recommendations and difficulties in the present review indicate the lines of inquiry for further study. The number of studies on desiccant-integrated dehumidification and cooling systems is progressively growing. These investigations support the possibility of using solid-desiccant or liquid-desiccant integrated innovative cooling as an alternative to conventional air conditioning. The CO_2 emissions from the desiccant integrated cooling system are almost 41% less than that of the VCR-based conventional cooling. It is crucial to design and choose the appropriate desiccant that is more energy-efficient, environmentally friendly, and cost-effective, as this cooling technology has recently been developed. More thorough research on the creation and assessment of sophisticated materials is still required to go ahead.

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