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Article

A review on progressive development in desiccant materials

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Abstract: Desiccant based comfort cooling has been very popular among the alternative cooling techniques that uses renewable solar heat or waste heat now become a good option to conventional cooling technology. The effective regeneration of desiccant materials used in the desiccant based dehumidification and cooling nearly about ambient conditions plays a crucial role in ameliorating the overall system cooling performance. The innovation in the desiccant materials that are nearly regenerated at ambient conditions by use of low temperature primary heat is the main aim of researchers to improve the dehumidification rate of the existing conventional desiccants. The non-conventional desiccant materials include composite desiccants, nano-porous inorganic materials and polymeric desiccants include in this review. Regeneration capability of the desiccant materials is its moisture rejection ability at low temperature primary heat source. It is found in earlier research that the appropriate selection regarding the type host matrix and immersed salts, composite desiccants can significantly improve dehumidification ability of the desiccants and its better regeneration at nearly ambient conditions. Furthermore, a good tolerance among the regeneration and adsorption capacity by tailoring textural properties of nano-porous inorganic materials is the demand of future desiccants. For polymeric desiccants, further progress in increasing its adsorptive dehumidification rate is also a demand of future dehumidification and cooling techniques designs. Currently limited materials available today can successfully satisfy the above demands. So, it right time to investigate more intensive researches in the field of development and evaluation of advanced materials to ameliorate the cost and energy savings in the field of dehumidification and cooling of the built environment.

Keywords: Dehumidification, desiccant materials, polymer, regeneration.

1. Introduction

Day by day energy demand of buildings used for residential and different commercial applications has been increasing exponentially. According to the survey, it is estimated that almost about 45-54% of total energy used by the building can be used only for the purpose of dehumidification and cooling i.e. maintaining thermal comfort within buildings. Traditional air conditioners mostly used electrical energy for its running can be produced mostly in fossil fuel based thermal power station. So, reduction in use of electricity used in cooling is the major challenge for the HVAC engineers and researchers in the coming days to reduce production of CO_2 [1-3].

So, desiccant cooling can be taken up as a potential alternate to the conventionally used

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vapor compression based traditional air conditioners [5-8]. As compared with the other traditionally used existing air conditioning system for residential and commercial purpose in market today, desiccant assisted dehumidification and cooling systems have several other significant advantages:

1. Desiccant assisted dehumidification and cooling cycles may be operating by application of freely available renewable solar energy of cheaply low temperature industrial waste heat energy resources.
2. Desiccant powered dehumidification and cooling system is eco-friendly as it eliminates the use of chlorofluoro based harmful refrigerant which are responsible for depleting the ozone layer.
3. Desiccant based cooling cycles does not require overcooling and reheating as both temperature and humidity controlled separately in sensible cooler and dehumidifier respectively. Moreover, it controls the rate of dehumidification in a better way by application of rotary desiccant dehumidifier as compared to traditional cooling.
4. Due to operation of desiccant cooling cycle nearly about ambient pressure due to only air as working substance, it avoids any leakage from system.
5. Due to existed dry atmosphere, it avoids any corrosion and wetting the carrier duct to convey air from system to air conditioned room.

Desiccants are generally the chemicals having affinity with the moisture present in the ambient humid air.

While desiccant laden matrix rotated moist air allowed passing through it at very slow rotating speed of dehumidifier. Due to pressure difference between moist air and dry desiccant surface, water vapor adsorbs over surface of desiccant. To make wheel working for the next cycle, reactivating heat has been supplied from low temperature primary energy sources like as freely available solar energy or comparatively cheaper industrial waste heat. So, the operating cost of desiccant assisted dehumidification and cooling system is very low as compared to the traditional cooling cycle. The overall performance of the system depends mainly on the effectiveness of the dehumidifier. It greatly governs by type of desiccant used and its regeneration temperature [9-11].

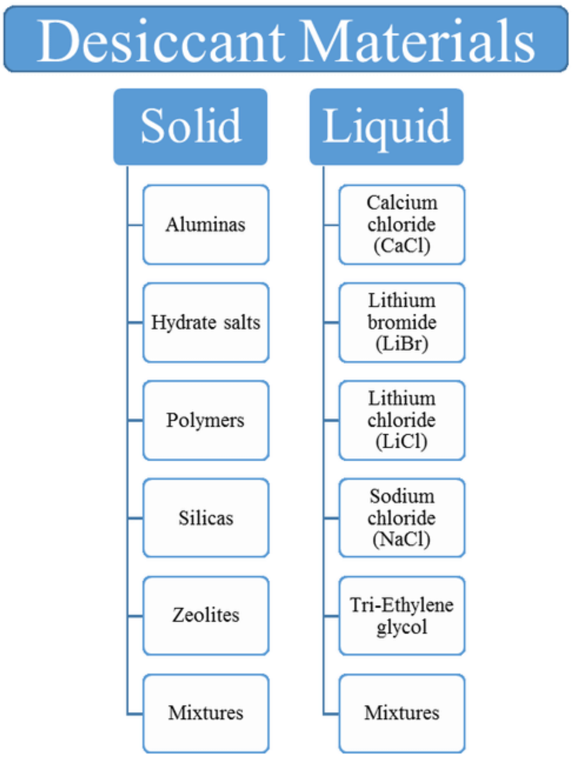

Figure 1. Difference between types of solid and liquid desiccant materials in desiccant cooling cycle.

The silica gel is mostly used as commonly applied desiccant material in desiccant dehumidification system due to its low cost and comparatively low reactivation temperature. But, to apply primary energy like solar heat or industrial waste heat major investigations regarding searching of desiccant materials that regenerate near ambient conditions are required to be investigated [12-15].

To the best of the authors' knowledge, there is rare comprehensive summary carried out previously by earlier researchers over to application of either solid desiccant or liquid desiccant materials (Figure 1). So, the current review enlighten the typical application and innovation about recently used desiccant types in desiccant powered air conditioning cycles are also commented as well as discussed in detail. In the end, major conclusions and perspectives towards further endeavors are summarized in favor of HVAC recent application in built environment.

In the traditional cooling system, moisture from humid air separated by passing it over condenser cooling coil whose temperature is maintained below the dew point temperature of incoming air. Available conditioned air then passed to the conditioned test room after if any post re-heating required (in case of overcooling) to maintain supply design conditions. However, this traditional approach of air conditioning inevitably makes substantial electrical energy loss owing to vapor compression, overcooling and reheating. Moreover, condensed water also create unhygienic environment due to wetness in the surrounding supply duct. The desiccant assisted dehumidification and cooling technique makes application of rotary dehumidifier which removes moisture from air by the process of chemical adsorption process. Numerous desiccant materials like as metal silicate, molecular sieve, silica gels, zeolites etc. are used to adsorb water vapor from the supply moist humid air into the small pores provided inside the desiccant matrix surface. Thus, desiccant dehumidification and cooling technology can effectively handle the humidity and temperature separately into the dehumidifier and sensible cooling coil. Moreover, the same eliminates the requirement of very temperature maintenance inside cooling coil for condensing the moisture and post reheating the supply air can save lot of energy for cooling. Use of freely available solar energy and low temperature industrial waste heat can save cost further to result in the economy operation of the system [16-18].

According to the previous investigations, the solid desiccant reactivation temperature was around 60–120°C. However, the regeneration temperature of the solid desiccant can be required near ambient by the use of advanced polymer based desiccant materials to effective use of low temperature primary heat source for effective regeneration of desiccant materials used in the rotary desiccant wheel.

Liquid desiccant assisted dehumidification air conditioning can have many advantages over conventionally used vapor compression based air conditioners like as handling the large mass of air as well provision of proper ventilation air rate for the built environment with the residential and commercial buildings. Furthermore, the application of liquid desiccant assisted dehumidification (very low dehumidification range) can advantageous to many commercial industries such as agriculture for elongated seed storage in attended ultra-dry built atmosphere, medicines, food processing and food storage, pharmaceutical laboratories etc. The advantages and disadvantages of liquid desiccant cooling [19-22] summarized as below:

1. The liquid desiccant can reactivate effectively at near ambient outdoor temperature, which makes effective use of freely available low grade primary energy sources like renewable solar heat for lowering the operating cost of the system.
2. The entire unit requires less space as compared to the traditional air conditioners.
3. It substantially decreases consumption of high grade electricity only for its running the fans and driving electrical motors for the same cooling capacity.
4. Defrosting eliminated completely as liquid desiccant materials having good antifreeze properties.
5. The humidity and temperature both are handled separately and effectively.

Along with above mentioned merits, it also has a few disadvantages as explained following:

1. The corrosive nature of liquid desiccant materials can corrode internal ducts and pipelines in the system.
2. Effective mist eliminators are needed as

carryover of desiccant fumes along with the conditioned air can cause severe health problem to the occupants.

3. Pumping power to circulate the liquid desiccant between regenerator and absorber is more as large volume of liquid desiccant solution.

7.

4. Liquid desiccant can cause the severe problem of crystallization in some typical applications.

5. The installation price of the system is much higher.

6. The first cost for the system is also more.

2. Use of desiccant materials in dehumidification

The construction of desiccant laden rotary desiccant dehumidifier is a slowly rotating wheel having matrix throughout its structure as shown in Figure 2. Due to this corrugated structure long air passages know as flutes are available for passing the air from one side to the other one. Total structure of wheel divided into two parts namely process air section and regeneration air section for carrying conditioning air as well as reactivation air respectively. The wheel is rotated around 8-12 RPH speed for providing sufficient time for adsorption of moist air while passing through it. There are many geometrical shapes are available for air channels like as triangle, sinusoidal, square etc. Mostly the ceramic and glass fiber are used as substrate materials which are porous in nature. The adsorption of water vapor form the humid air is takes place due to the pressure difference between cold room air (having high vapor pressure) and comparatively hot desiccant matrix (having low vapor pressure). It is common phenomenon that water vapor travels from high pressure to low pressure as well as natural attractive forces play a key role in air dehumidification. Thus, it will conduct heat and mass exchange with the desiccant and substrate due to huge temperature difference among them. Mainly the dehumidification and regeneration efficiency of the desiccant wheel are affected by the effectiveness of the heat and mass transfer in the air channels between desiccant surface and room air passing over it. Previous investigations show that the sinusoidal air channel geometry shapes as well as thermo-physical property of substrate materials has a substantial influence over the adsorption rate of rotary desiccant wheel. Some researchers mainly focused to observe the influence of different channel shapes of air flutes and type of substrate material over adsorption rate of dehumidifier. As desiccant wheel demand for suppleness of substrate materials, stationery desiccant bed systems are opted as a promising option [23-25].

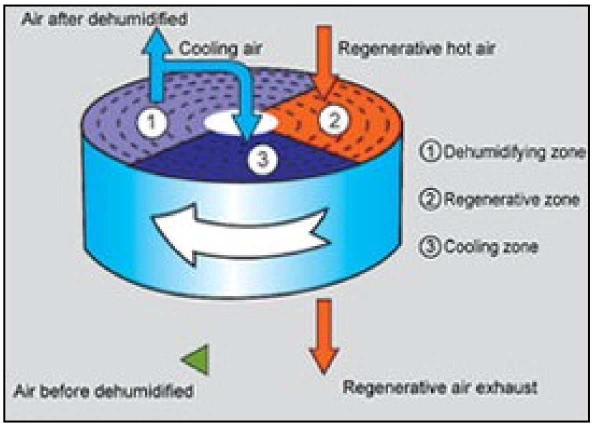

Figure 2. Working of rotary desiccant wheel.

Working of liquid desiccant dehumidification and cooling system is quite similar to the solid desiccant except the desiccant type used. It uses liquid desiccant like calcium chloride, ethylene glycol etc. in its liquid state. In liquid desiccant cooling two main components are required namely absorber and regenerator. There are different types of liquid desiccant cooling system are in existing according to the its working principle namely packed beds, spray towers and falling film columns etc. Liquid desiccant cooling can handle large air volume flow rates while circulating through the large surface areas per unit volume for contact between air and the desiccant sprayed over humid air for effective moisture removal. The carryover of desiccant fumes with the condition air stream at supply is a major concern in liquid dehumidification and cooling systems, which is slightly due to drift and to vaporization of some soluble solutions at high temperatures, although the typical advanced innovative designs of liquid desiccant based dehumidification and cooling systems that claim for zero carryover. In a dehumidification system as shown in Figure 3, the absorber and regenerator are commonly coupled through a liquid-to-liquid heat exchanger to lower the regenerator residual heat to the evaporator. This slightly cools the strong solution by application of leaving weak solution. It ameliorates the dehumidification rate by 8-16% for the system.

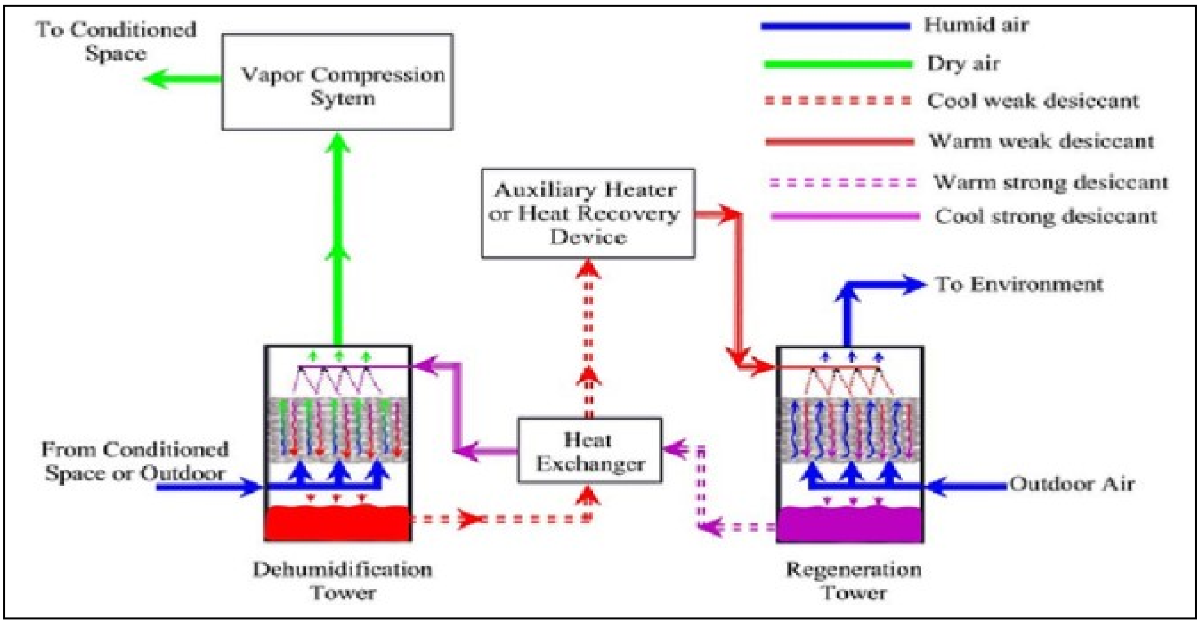

Figure 3. Working of liquid desiccant cooling system.

Thus, in both solid as well as liquid desiccant based dehumidification systems performance and effectiveness were greatly governed by the reactivation temperature of particular desiccant type. The key element for selecting justified desiccant type is that the ability to absorb and hold large amount of water vapor per lowest unit weight of the same. It must be desorbed properly by minimum heat supply. The other thermo-physical properties of the desiccant materials such as density, vapor pressure, etc. of different desiccant materials can be enhanced greatly by mixing two or more materials by hybridized them together. This can be also known as a composite desiccant [26-27].

3. Types of adsorbent in desiccant dehumidification

Desiccant powered air conditioning first adsorbs the moist air and then cooling of the same can be carried out in sensible coolers. For make dehumidifier continually in operation, reactivation of the same can be carried out by passing hot regeneration air through the reactivation section of the dehumidifier. The energy required by the reactivation air can be supplied with low temperature primary energy sources like as renewable solar energy and low temperature industrial waste heat. Thus, for to have better performance of the overall system, higher effectiveness of desiccant wheel play a major role. This can be achieved by efficient energy supply at low regeneration temperature by use of freely available primary energy sources. Moreover, it is desirable that the regeneration temperature should be around 45-50°C for efficient utilization of waste heat sources [28-29].

The desiccant materials either adsorb or absorb according to its typical type as a solid or liquid that efficiently control moisture level of conditioned indoor space. These materials are applied particularly in typical applications like as pharmaceutical or agricultural applications where low dew point for dehumidification of air is desirable. The quality of a good desiccant material can be judged by its equilibrium vapor pressure, which is water vapor pressure that is in equilibrium with surface desiccant material over its substrate. Some other important parameters which are responsible for desiccant materials better performance are:

1. Energy storage density.
2. Comparatively low regeneration temperature.

3. Ease of availability.
4. Cheaper in cost.
5. Desorption temperature.

A good desiccant should have the following properties:

1. Large saturation adsorption capacity.
2. Low reactivation temperature.
3. Low viscosity for better circulation.
4. High heat transfer rate.
5. Non-volatile.
6. Non-corrosive.
7. Odorless.
8. Chemically stable.
9. Inexpensive.

Above described desirable characteristics of the desiccant material play an important role in ameliorated performance of the desiccant laden rotary dehumidifier. Description about some important types desiccant materials used in various applications in different desiccant cooling cycles are discussed as follows:

i. Silica gel

The traditional desiccant material used for common applications in dehumidification is silica gel. Silica gel physically removes water vapor from air into its internal pores. The adsorption and desorption characteristics of different silica gels typically changes according to their variety of production methods. The variable adsorption performance suggested that the textural properties of silica gel have a predominant action in dehumidification. Silica gel has typically substantially high moisture adsorption capacity because of its micro-porous structure of internal interlocking cavities that provides large internal surface area for communicating the moist air. Silica gel interacts with water vapor presented to the moist air by passing it over its large surface area via hydrogen bonding interactions. The significant number of active sites makes silica gel a promising material for effective air drying in all typical applications. However, due to the mild hydrogen bonding between OH groups and H_2O, silica gel is preferred less for deep dehumidification typically in applications where ultra-low humidity desirable. It is also seen through previous investigations that the adsorption capacity of silica gel lowers with rise in adsorption temperature owing to its poor physisorptive nature. Silica gel is not susceptible to structural damage in a mild reactivation condition, but a loss of surface silanol groups for moisture adsorption occurs at a very high reactivation temperature beyond 150°C.

ii. Activated carbon

Activated carbon is one of the most important adsorbents that perform key role in most of commercial applications. Taking merit of porous materials with large internal surface areas and huge pore volumes, activated carbon and carbon-based materials are still investigated for their better adsorption dehumidification. The textural properties of activated carbon can be change according to the different carbon sources and various activation methods. The hydrophobic nature of the typical graphene structure in some activated carbon structure indicates its poor dehumidification performance at reduced relative pressures of water vapor in moist air. Here, it is important to note that the surface chemical properties of activated carbon, including surface functional group types and density, can be improved further by different activation processes at variable environmental conditions. With the improvement in the structure of activated carbon with little addition of silica for a more hydrophilic surface, a substantial amelioration in dehumidification performance has marked in previous literatures.

iii. Zeolites

Zeolites is found most suitable for it's the ultra-low adsorption capacity. Zeolites that are in HVAC market application for air drying nowadays is categorized as A, X, and Y. Zeolites possess remarkably high adsorption capacity due to their typical surface chemistry and specific crystalline pore structures. Zeolites can found with very low dew points or ultra-dehumidification of air due to the strong zeolite–water vapor molecule interaction. Furthermore, the reactivation of zeolites at nearly ambient conditions is found rate as the stronger bond strength of water molecules with allocation sites in the zeolite. In earlier investigations it is found that the required heat of adsorption of zeolite adsorbents up to 56% higher than the latent heat of vaporization was cited in previous literature that means it demand exceptionally large reactivation energy have been demanded for its complete regeneration. Therefore, the limitation of using zeolites as the desiccant material in dehumidifier is that the very large energy-intensive regeneration requirement owing to demand of large reactivation temperature.

iv. Metal foam

As a kind of porous media, metal foam has been put special attraction for its dehumidification properties typically for its low density and improved thermal, mechanical, and acoustic properties. Mainly the exceptionally better heat transfer performance of metal foam was investigated at large by most of the previous investigators. Typically large-size internal pore diameter and very good porosity are the main structural unique characteristic that metal foam having and the porosity of commonly used metal foam type may have up to 48–82%. Metal foam can be further categorized into two important type which are commonly known as open-cell and closed-cell foam. But open-cell metal foams are applicable mostly in wide requirements than the closed-cell metal foams, as the former consist of very large internal specific surface area, exceptionally better thermal conductivity and abundantly large flow path area. If the substrate of internal matrix of rotary dehumidifier is laden with open-cell metal foam then the desorption characteristics of the dehumidifier is found still better.

v. Calcium Chloride

Calcium chloride is a typical ionic halide which serves calcium ion in aqueous solution and at nearly ambient conditions it is available in a solid state. It is commonly manufactured by direct reaction of limestone with hydrochloric acid but in huge demand it is manufactured as a by-product of solvey process. Its evaporation temperature is found around 1395°C which is exceptionally very high along with its comparatively low as 2.15 g/cc density.

vi. Lithium Chloride

Lithium chloride is an ionic salt which is mostly used in variety of commercial applications required variable dehumidification rate including different cooling requirements. It has typically good hygroscopic performance and exceptionally high solubility around 83 g/100 ml at 20°C found typically in polar solvents. Its evaporation point temperature is found very high around 1382°C with comparatively low about 2.068 g/cc density. The crystallization line of lithium chloride and water vapor solution is having high mass fraction of lithium chloride and lowering its water content.

vii. Composite adsorbents

Composite materials are made up of mixing two different kinds of hygroscopic salts into the pores of the host, i.e., a porous desiccant material in the present case. The hygroscopic salts are the commonly used nitrates, sulphates and haloids etc. that are typically consists of high water absorption or removal properties oppositely they found chemically unstable at exceptionally larger humidity ratios due to lyolysis, so porous adsorbents with chemical stable properties such as silica gels, molecular sieve, activated carbon, metal and meso-porous silicates and natural rocks are mostly applied as host material. Earlier developed most composite desiccants used for dehumidification applications in thermal comfort productions and earlier investigations shown that the composite desiccants can have better COP as well as water removal properties. A number of composite adsorbent were developed in the past ten years to ameliorate its water vapor removal rate and effectiveness. The observations indicate that the composite desiccant materials can be regenerated near ambient conditions. About 82% of adsorbed water could be desorbed from these composite desiccant materials at a very low temperature range of 55 to 70°C.

4. Future needs for adsorbents

The major challenges faced today by different adsorbents are their huge demand of regeneration thermal energy to regenerate adsorbents completely. The use of freely available renewable solar energy and low temperature industrial waste heat for adsorbents reactivation will make the system running cost competitive and attractive in today's HVAC market. The application of adsorbents in different cooling techniques can solve lot of environmental problems well, as it can also lower need of high grade electricity for traditional vapor compression cycle and inferior IAQ (indoor air quality). Even if the major investigation in liquid absorbents innovations have been made previously by the different researchers in many parts of world but a few further actions still needed to be taken in order to make this underestimate cooling technology to make more market penetrable and competitive [30]. Some of future innovations and investigations needs are as follows:

1. Cost-effective, noncorrosive, and nontoxic liquid absorbents needed to be invented. These materials must have available with smaller surface tensions so that they can wet well with the surface in contact of the dehumidifier and regenerator.

2. The absorbents should have lower viscosity so that demanded pumping power for its circulation through the system can be lowered substantially. Also these materials should be required chemically stable at variable temperature limits.

3. The effectiveness of regenerator needs to be ameliorated by application of different strategies that consist of mainly multiple-effect boilers and vapor compression distillation. Different alternative energy sources including freely available renewable solar heat and low temperature industrial waste heat should be applied efficiently for the complete reactivation of absorbents.

4. Surface enhancements can be provided by efficient use of the extended metal surfaces like as fins to modify greatly the improved design of dehumidifier and regenerator for maximum possible heat and mass transfer rate.

5. Innovative technology development with regard to better use of software for simulation and modeling, Zero carry-over considerations in typical improved design, innovative advanced sorption materials etc.

6. Performance map should be performed for various categories of adsorbents used under variable climatic and different room operating conditions.

7. Major challenges in the working of adsorption cooling is namely pressure drop in solid desiccant and carryover of liquid desiccant fumes by air stream may be completely removed by optimizing the design of system. The design optimization of adsorption cooling will greatly affect the outlook from the technical and energy saving point of view.

8. The application of composite desiccant materials may ameliorate the moisture adsorption capacity of the adsorption material to the great extent.

Further research and development of adsorbent type used in the field of HVAC demands major efforts from the established experts in this area, which are familiar and expertise in operation of these systems. Besides showing the current trends of the dehumidification requirement along with the cooling in connection with producing indoor comfort shows the major variation of key operating and design parameters discussed in detail above is a simple yet powerful tool to optimum design of a desiccant based hybrid air-conditioning system. Energy efficiency enhancement potentials due to the system level coupling of the desiccant dehumidifiers with the traditional HVAC units of vapor compression air-conditioning systems are still needed to be analyzed. Innovative design activities need to be developed to make this technology accessible to all people in different parts of the worlds through cost reduction and variable energy saving approach by making HVAC market more competitive with this innovative and efficient cooling technology.

5. Conclusions

The desiccant powered dehumidification and air conditioning system may driven from low grade renewable solar heat or industrial waste heat can established as promising alternative to the conventional cooling system. The effective use of desiccant material assists in substantial moisture reduction in the conditioned air in the system. To search for the optimal use of the desiccant material, a comprehensive comparison for different water adsorption quantity and reactivation ability among various advanced desiccants was discussed in detail in the review. For instance, composite desiccant materials have ameliorated water vapor removal capacity with the support of impregnated salts. Moreover, by justified selection of host matrix and immersed salts, i.e. clay/chlorine salt composite materials, the resulted reactivation obtained as minimum as around 45°C (near ambient conditions) can be achieved by effective use of the same. Furthermore, a good result can be obtained by duel benefit among the low reactivation temperature and water removal rate by delicately tailoring textural properties of nano-porous type many inorganic desiccant materials types. For proper use of polymeric type desiccants together with the advances in the material science and with the proper help of molecular simulation, a large step forward many practical applications in adsorptive dehumidification particularly in pharmaceutical and agricultural (besides air conditioning) will be anticipated. The further development in advanced desiccant technology is an ongoing progress that mainly innovate different desiccant materials and it has attaining good competition in the HVAC market. It appears to be reliable, safe, and environmental friendly air conditioning technique as per the needs of our society in both residential and commercial HVAC markets.

Conflicts of Interest

The authors declare no conflict of interest.

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