International Journal of Advanced Materials Research
Vol. 5, No. 2, 2019, pp. 31-37
http://www.aiscience.org/journal/ijamr
ISSN: 2381-6805 (Print); ISSN: 2381-6813 (Online)

An Overview on Recent Development in Desiccant Materials

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Abstract

Desiccant based cooling and dehumidification systems have gained increasing interest as an alternative air conditioning technology. Performance of desiccant plays a crucial role in overall performance of the overall system, especially in terms of dehumidification and regeneration capacity. It is desirable to explore desiccant materials that are possessing high adsorption capacity and good regeneration ability. Thus, this review summarizes recent researches and developments on various desiccant materials that can be adopted in desiccant based cooling systems. The materials include composite desiccants, nanoporous inorganic materials and polymeric desiccants. Regeneration ability is also considered for full use of low grade thermal energy. It is also seen that by proper selection of host matrix and immersed salts, composite desiccants have improved capacity of dehumidification and regeneration. Besides, a good balance can be reached between regeneration and adsorption capacity by tailoring textural properties of nanoporous inorganic materials. For polymeric desiccants, further progress in adsorptive dehumidification will be anticipated. Though some novel materials approach requirements for desiccant assisted systems, limited material currently available can perfectly satisfy all the required demands. In this case, more intensive researches in the field of development and evaluation of advanced materials are still required.

Keywords

Adsorption, COP, Desiccant Dehumidification, Desorption, Reactivation

Received: January 27, 2019 / Accepted: August 7, 2019 / Published online: September 6, 2019

1. Introduction

With the rapid growth of economy and society, our modern life style and industry consume large amounts of energy for cooling the residential and industrial buildings. According to the latest statistics, energy consumption in air conditioning is estimated to 48% of the whole civil and commercial buildings [1]. Meanwhile, the depletion of fossil fuels and the threat of global warming over the last decades have challenged air conditioning industry to develop new cooling technologies to assist or even replace the conventional air conditioning systems based on VCR. Therefore, numerous alternative cooling technologies have been developed to substitute conventional VC systems, and desiccant cooling is one of them. Compared with other systems, desiccant cooling systems have several significant merits [2-5]:

1. Desiccant cooling systems can be operated by use of low grade thermal energy sources like solar energy.
2. Desiccant cooling system is environmentally friendly as it does not use CFC based refrigerants which are responsible for global warming.
3. Over cooling and reheating of conditioned air supply can be avoided by use of desiccant desorption to control the humidity in air.
4. Leakage is avoided as desiccant cooling system operated nearly at ambient pressure.
5. Less prone to corrosion and wetting the supply duct.

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A desiccant cooling system consists of passing humid (and warm) air through a desiccant laden dehumidifier rotary wheel for drying and through a cooler for sensible cooling to provide conditioned air. The desiccant material used in the rotary dehumidifier becomes saturated with water and needs to be regenerated with hot air provided by an energy source (e.g., sun, natural gas, waste heat, or electricity). The cost, efficiency, and durability of a desiccant cooling/dehumidification system depend on those of the components used in the system. The desiccant dehumidifier is a major component in the system. After several years of research, it is well understood that the performance of a desiccant dehumidifier depends strongly on the properties of its desiccant and the geometry of the matrix [6]. Usually, microporous silica gel has been used as the research baseline desiccant for solar-regenerated desiccant cooling applications [7]. Lithium chloride impregnated wheels, commercially available dehumidifiers, have been used in desiccant cooling systems [8]. Advanced dehumidifiers for desiccant cooling applications should have parallel passage geometries, such as parallel plate or corrugated to be compact and efficient with low pressure drops.

To the authors' knowledge, there is rare comprehensive summary of these newly developed solid desiccant materials (Figure 1). Therefore, in this article, recent emerging researches relevant to the development of high-performance desiccants are overviewed. Their characteristics and possible applications in desiccant based cooling and dehumidification systems are also compared and discussed. In the end, major conclusions and perspectives towards further endeavors are summarized.

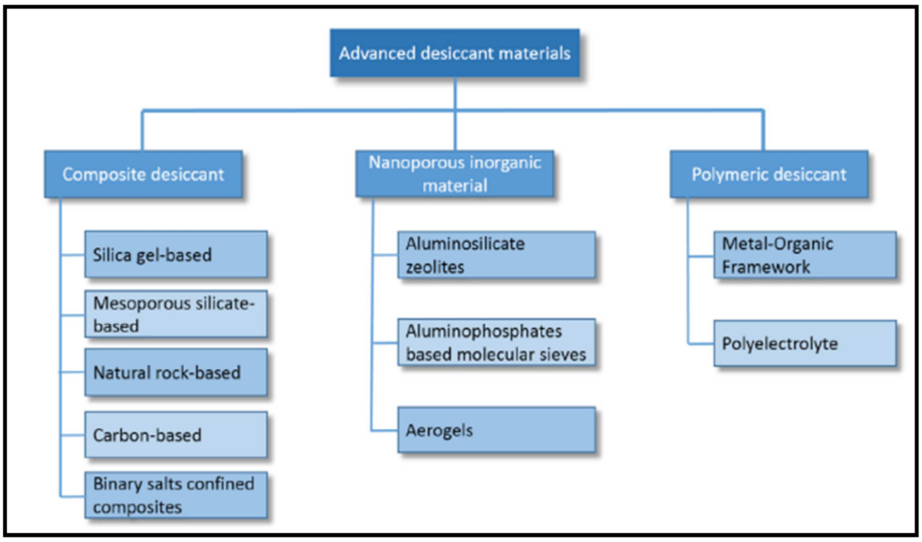

Figure 1. Classification of advanced developed desiccant materials used in desiccant cooling technologies.

The conventional air dehumidification methods include moisture condensing method, desiccant-wheel method, and liquid-desiccant method. Among them, the moisture-condensing method, the majority, removes the moisture in the air through the condensation, which is achieved by reducing the air temperature below its dew point temperature (overcooling) and then the cold and dry air is reheated to an acceptable supply temperature [9-13]. However, this approach inevitably causes energy waste due to overcooling and reheating, and bacteria and mold growth on the cooling coils due to condensate water [14]. The desiccant-wheel method uses solid desiccants such as silica gels, zeolites, and others to directly adsorb water vapor from the air into the small pores inside the desiccant medium. Based on this principle, the desiccant-wheel system can regulate air temperature and humidity separately [15, 16]. Thus, the desiccant-wheel system has an extensive conditioning systems are eliminated. These not only save electricity but also reduce the size of the system if waste energy and solar energy can be used. According to the literature [17], the solid desiccant regeneration temperature was around 65–140°C. However, the regeneration temperature of the solid desiccant can be relatively higher for sufficient and faster dehumidification.

Liquid desiccant cooling technology having great number of merits over traditional cooling systems such as no condensation requirement that eliminates growth of fungi or other harmful bacterial growth avoids various health problems to the occupants. This benefit of liquid desiccant cooling can advantageous to many industries such as medicines, food storage, laboratories etc. Merits and limitations of liquid desiccant cooling [9] summarized as follows:

1. The liquid desiccant can regenerate at ambient temperature, which makes use of freely available low grade energy sources like renewable solar heat.

2. The entire unit is small as well as compact.
3. It lowers the use of electrical power and has high moisture removal capacity.
4. No freezing or frosting occurs at lower temperature as liquid desiccant materials are good antifreeze.
5. The latent and sensible heat loads are handled separately and effectively.

Along with above mentioned merits, it also has limitations as described below:

1. The corrosive nature of liquid desiccant materials can damage the system.
2. Mist eliminators are needed as carryover can cause sever health problem to the occupants.
3. Larger pumping power is required as to pump large volume of liquid desiccant solution.
4. Some liquid desiccant may face the problem of crystallization.
5. The initial cost of the system is higher.
6. The initial cost for the system is higher.

2. Use of Desiccant Material in Dehumidification

In general, the bulk of a rotary desiccant wheel dehumidification system is a cylindrical rotary wheel, which is obtained by rolling up the corrugated porous fiber sheet coated with desiccant. During the forming process of the corrugated porous fiber sheet, two pieces of long flat porous fiber sheets are prepared. One piece of flat porous fiber sheet is processed to corrugated shape in a corrugating machine. Then it is bonded to the other crude one to maintain the corrugated shape. In the cylindrical rotary wheel, a large number of parallel channels are obtained, and the cross section shape of single air channel is a sinusoidal shape, as shown in Figure 1. Usually, the main raw materials used as substrate are porous ceramic fiber paper and glass fiber paper. In the rotary desiccant wheel dehumidification system, when the process air or regeneration air passes through the air channels of desiccant wheel, they will conduct heat and mass exchange with the desiccant and substrate. So the dehumidification and regeneration efficiency of the desiccant wheel are affected by the performance of the heat and mass transfer in the air channels. To get deep insight into dehumidification performance of desiccant wheel, single air channel should be selected as an object [18].

From the earlier researches, it can be seen that cross-section shape of air channel in a conventional desiccant wheel is usually sinusoidal, and thermo-physical property of substrate materials has a great effect on the dehumidification performance of desiccant wheel. Some researchers have attempted to study the effect of various cross-section shapes of air channel and substrate materials on the dehumidification performance. Because of desiccant wheel having a requirement for suppleness of substrate materials, non-rotary solid desiccant dehumidification systems are selected as an alternative.

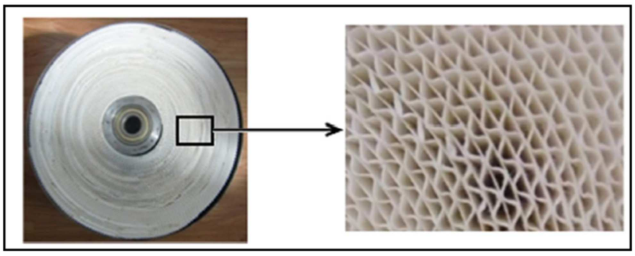

Figure 2. Use of desiccant material in rotary desiccant dehumidifier.

The liquid desiccant cooling use component similar to those in solid desiccant cooling but it operates on desiccant in liquid state (e.g. packed beds, spray towers and falling film columns). These should be designed to handle large process air and low desiccant flow rates [19-22]. An important consideration in the design of contacting equipments is that the air pressure drop through the absorber should be as small as possible, while providing large surface areas per unit volume for contact between air and the desiccant. The carryover of desiccant with the air stream is a problem in liquid systems, partly due to drift and to vaporization of some solutions at high temperatures, although there are some systems that claim for zero carryover. In a dehumidification system as shown in Figure3, the absorber and regenerator are generally linked through a liquid-to-liquid heat exchanger to reduce the regenerator residual heat to the conditioner. It pre-cools the warm concentrated solution transferred to the conditioner using the cool dilute desiccant from the outlet of the conditioner. This improves the dehumidifier performance and reduces the heat input to regenerator by 10-15%, thus improving the thermal efficiency of the system. Further improvements are possible by internally cooling the absorber as shown in Figure 3.

The performance and development of desiccant cooling systems strongly depends on the used desiccant materials. The thermo-physical properties of these materials affect the performance of the system significantly. The key parameter for the selection of a desiccant material is that it should have the ability to absorb and hold large amount of water vapor. It should be desorbed easily by providing heat input. The properties such as density, vapor pressure, etc. of different desiccant materials can be enhanced by mixing two or more materials together. The mixed desiccants are termed as composite desiccants. Many researchers have studied the properties of composite desiccant materials in order to study their effects on dehumidification performance of the system [20-22].

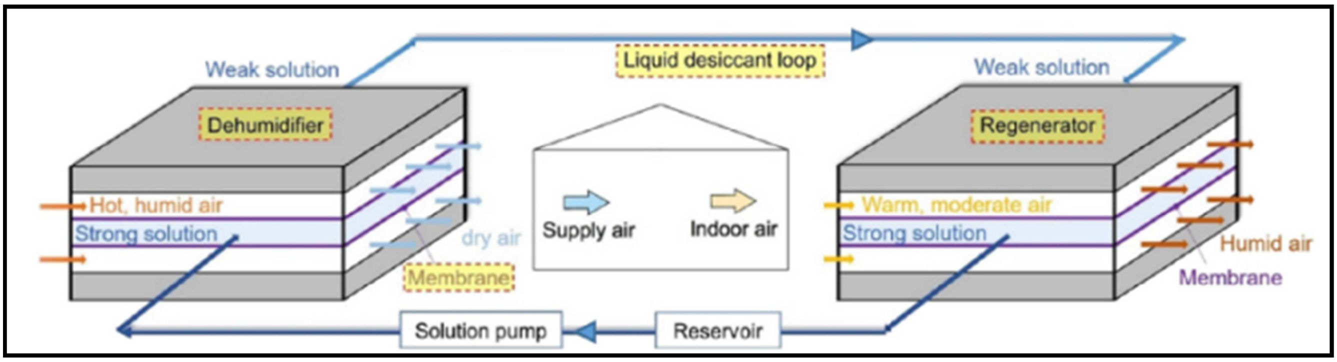

Figure 3. Use of desiccant materials in liquid desiccant cooling system.

3. Adsorbents Used in Desiccant Cooling

In a desiccant assisted cooling and dehumidification system, the process air is dehumidified in an adsorption process by a solid desiccant material, and then cooled by evaporative cooling to desired temperature. To reuse the desiccant, water vapor adsorbed is driven off through a regeneration process. This process is realized by heating from thermal energy such as electricity, waste heat, or renewable energy. Thus, adsorption and regeneration performance of the desiccant material can greatly affect dehumidification of the desiccant dehumidifier used in the system. In order to improve the performance of the overall system, the desiccant is expected to have large water adsorption capacity at a defined adsorption temperature and be easily-regenerated at a relatively low regeneration temperature. Besides, it is expected that the regeneration temperature is less than 110°C, considering that waste heat resources in the temperature range of 60-85°C account for 60-70% of the total ones [23-24].

The desiccant materials either adsorb or absorb according to its solid or liquid which attracts moisture. These materials are used in place where low dew point for dehumidification of air is required. The strength of desiccant materials can be measured by its equilibrium vapor pressure, which is water vapor pressure that is in equilibrium with desiccant material. Some other parameters which indicate desiccant materials performance are:

1. Energy storage density.
2. Temperature for reactivation.
3. Availability.
4. Cost.
5. Desorption temperature.

A good desiccant should have the following properties:

1. Large saturation absorption capacity.
2. Low regeneration temperature.
3. Low viscosity.
4. High heat transfer.
5. Non-volatile.
6. Non-corrosive.
7. Odorless.
8. Stable.
9. Inexpensive.

Characteristics of the adsorbate play an important role in adsorption. Description about some important desiccant materials used in desiccant cooling are described as follows:

i. Silica gel

One conventional adsorbent for dehumidification is silica gel. Silica gel physically adsorbs moisture from air into its internal pores. The adsorption and desorption characteristics of different silica gels may vary based on their manufacturing procedures. The variable adsorption performance suggested that the textural properties of silica gel played a significant role in dehumidification. Silica gel has very high moisture adsorption capacity because of its micro-porous structure of internal interlocking cavities, which provide a high internal surface area. Silica gel interacts with H_2O through the significant amount of surface via hydrogen bonding interactions. The significant number of active sites makes silica gel a promising material for air dehumidification at high humidity. However, due to the mild hydrogen bonding between OH groups and H_2O, silica gel is not suitable for deep dehumidification. It should also be pointed out that the adsorption capacity of silica gel decreases with an increase in adsorption temperature due to its weak physisorptive nature. Silica gel is not susceptible to structural damage in a mild regeneration condition, but a loss of surface silanol groups for moisture adsorption occurs at a high regeneration temperature.

ii. Activated carbon

Activated carbon is one of the most important adsorbents dominating the commercial use of adsorption. Taking advantage of porous materials with very high surface areas and large pore volumes, activated carbon and carbon-based materials have been studied for adsorption dehumidification. The textural properties of activated carbon vary with the carbon sources and activation methods. The hydrophobic nature of the perfect graphene structure in some activated carbon shows a low adsorption capacity of H_2O at low relative pressures of water vapor. However, it is worth noting that the surface chemical properties of activated carbon, including surface functional group types and density, can be modified by different activation processes at variable conditions. With the modification of activated carbon with silica for a more hydrophilic surface, a significantly improved adsorption capacity was reported.

iii. Zeolites

Zeolites play an enabling role in deep dehumidification. Zeolites that are in commercial use for air dehumidification today are types A, X, and Y. Zeolites possess special adsorption properties due to their unique surface chemistry and crystalline pore structures Zeolites can achieve low dew points or deep dehumidification of air due to the strong zeolite–H_2O interaction. However, the regeneration of zeolites at low temperatures is difficult because the bond of water molecules with Al cation sites in the zeolite is quite strong. In previous study it is observed, a heat of adsorption of zeolite adsorbents up to 50% greater than the latent heat of vaporization was reported, which indirectly suggested that a high desorption energy is required for regeneration. Therefore, one of the drawbacks of using zeolites as the dehumidification adsorbent is the energy-intensive regeneration due to the required high desorption temperature.

iv. Metal foam

As a kind of porous media, metal foam has drawn extensive attention as desiccant material for the low density and special thermal, mechanical, and acoustic properties. Particularly, the heat transfer performance of metal foam has been studied widely by a number of researchers. Large-size pore diameter and high porosity are the main structural features of metal foam, and the porosity of common metal foam can reach 45–80%. Metal foam can be classified as open-cell and closed-cell foam. But open-cell metal foams are used more widely than closed-cell metal foams, as the former have high specific surface area, relatively high thermal conductivity and abundant flow path. If the substrate of desiccant wheel is made of open-cell metal foam, the dehumidification performance of the desiccant wheel will be considerable.

v. Calcium Chloride

Calcium chloride is a typical ionic halide which serves calcium ion in aqueous solution and at room temperature it is a solid. It is generally produced by direct reaction of limestone with hydrochloric acid but in large quantities it is produced as a byproduct of solvey process. It has a boiling point temperature of 1395°C with 2.15g/cc density.

vi. Lithium Chloride

Lithium chloride is an ionic salt that is widely used in air-conditioning systems. It has better hygroscopic properties and amazing solubility of about 83g/100 ml at 20°C in polar solvents. It has a boiling point temperature of 1382°C with 2.068g/cc density. The crystallization line of LiCl-H_2O solution is an increasing mass fraction of Li-Cl and reducing water content

vii. Composite adsorbents

Composite materials are generally formed by the impregnation of hygroscopic salts into the pores of the host, i.e., a porous desiccant material in this case. The hygroscopic salts (nitrates, sulphates and haloids etc.) possess high water adsorption characteristics but they are unstable at higher humidity ratios due to lyolysis, so porous desiccant materials with stable characteristics like silica gels, activated carbon, mesoporous silicates and natural rocks are used as host material. Previously investigated some composite desiccants for cooling applications and reported that the composite desiccants achieved high COP as well as water adsorption characteristics. A number of composite desiccant materials have been developed in the past few years to improve the performance. The results showed that the composite desiccant materials have lower desorption temperature. About 80% of desorbed water could be desorbed from these composite desiccant materials at a temperature between 70 and 80°C.

4. Future Needs

The limitation faced by desiccant system is availability of regenerating heat to regenerate desiccant material. But the use of solar energy and waste heat for regeneration of desiccant material will make the system more economical. The use of desiccant system can solve lot of environmental problems well, as it can also minimize the high demand of electrical energy for conventional air-conditioning system and poor indoor air quality. Although a number of developments had been made in liquid desiccant cooling technology but a number of steps still need to be taken in order to make this technology more market accessible. Some of future research and development needs are:

1. Cost-effective, noncorrosive, and nontoxic liquid desiccant materials need to be developed. These materials must have relatively low surface tensions so that they can easily wet the surface of the dehumidifier and regenerator.
2. The desiccant materials should have less viscosity so that required pumping power can be reduced. Also these materials should be stable.
3. The effectiveness of regenerator needs to be improved using several approaches including multiple-effect boilers and vapor compression distillation. Different alternative energy sources should be utilized for regeneration purpose.
4. Surface enhancements extended surfaces such as fins should be used to modify the design of dehumidifier and regenerator for better heat and mass transfer.
5. Technology development in terms of software for modeling, Zero carry-over design, new sorption materials etc.
6. Performance map should be carried out for the types of desiccant used under different environmental and operational conditions
7. Some problems in desiccant system such as pressure drop in solid desiccant and carryover of liquid desiccant by air stream may be eliminated or reduced by optimization of the design of desiccant system. The design optimization of desiccant system will enhance the potential from the technical and energy saving point of view.
8. The use of composite desiccant materials may improve the moisture adsorption capacity of the material.

Research and development of desiccant used in the field of air conditioning requires more efforts from experts in the area, which are familiar to these systems. Design activities need to be developed to make this technology accessible to all people in different parts of the worlds.

5. Conclusions

In desiccant assisted air conditioning, which can be driven by low grade heat, is considered as a promising method for assuring clean and economical air conditioning. The main objective for using desiccant materials is to remove latent heat in predetermined cycles. To find the optimal desiccant, a comprehensive comparison of water adsorption quantity and regeneration ability between different desiccants mentioned has been explained in the article. For instance, composite desiccant materials have improved water adsorption capacity with the support of impregnated salts. Moreover, by proper selection of host matrix and immersed salts, i.e. clay/chlorine salt composite materials, regeneration temperature as low as 40°C can be achieved. In addition, a good balance can be reached between the regeneration and water sorption capacity by delicately tailoring textural properties of nano-porous inorganic materials. For polymeric desiccants together with the development of material science and help of molecular simulation, a large step forward practical application in adsorptive dehumidification will be anticipated. The development in desiccant technology is in progress in terms of its desiccant materials and it has attaining stability in the market. It appears to be reliable, safe, and environmental friendly according to the needs of our society.

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