Renewable and Sustainable Energy Reviews 59 (2016) 73–83

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Solid desiccant dehumidification and regeneration methods—A review

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ARTICLE INFO

Article history:
Received 8 December 2014
Received in revised form
10 November 2015
Accepted 27 December 2015
Available online 18 January 2016

Keywords:
Dehumidifier
Regeneration
Solar concentrator
Solid desiccant

ABSTRACT

Desiccant dehumidification system is an alternate option against conventional dehumidification system in hot and humid climates. Conventional dehumidification systems have many drawbacks that include high power consumption and increase the chlorofluorocarbon (CFC) level in the environment and major contribute to depletion of ozone layer. This paper discuss the functioning of dehumidification, cooling and air-conditioning systems using various solid desiccant with focus on the use of solar energy for dehumidification of humid air and regeneration of solid desiccant wheel. A comparative study of various dehumidification, cooling and air-conditioning systems show that solid desiccant has low operating and maintenance cost and is environment friendly.

Contents

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http://dx.doi.org/10.1016/j.rser.2015.12.264
1364-0321/

1. Introduction

In tropical countries, increasing demand for active air-conditioning has lead to a large consumption of electric power (as compared to the energy demand for the sensible cooling of air). The high humidity in the tropics results in a significantly high air dehumidification load. Separate handling of the dehumidification load and sensible cooling load can significantly reduce the requirement of power for air-conditioning [1] if the dehumidification is done by solar thermal or waste heat recovery instead of using electricity. Desiccant cooling and air-conditioning systems that use solid or liquid desiccant are an interesting substitute [2–10] to an electrically driven vapor compression cooling system [2–10]. Heat requirement can be satisfied by supplying thermal waste [11] and solar energy [7,12] which are low grade energy system. Development of conventional desiccant [13–17], natural desiccant [18], bio-desiccant [19–23] and composite desiccant like silica gel and lithium chloride [24–39] have been the area of investigation relates to general aspects of solid desiccants and their areas.

Mathematical modeling, thermal analysis and experimental investigations have been performed over the past several by many researchers have focused on various aspects of the desiccant dehumidification [40]. These includes the desiccant material studies [41–44], rotary desiccant dehumidification and air conditioning processes [45–52] and performance modeling of desiccant wheels [53–57].

Air dehumidification is crucial aspect for increasing durability of products because dry air is used for improving the process, product or conditions in large industries such as food production, pharmaceutical production, industrial chemicals production etc. It is also required in goods storage, packaging equipment rooms, organic plant, inorganic products and hygroscopic raw materials storage [58].

Researchers have been used variety of dehumidification techniques only a few out of these have been listed in this paper. Conventional dehumidification based on vapor compression refrigeration system suffers from the disadvantage that the system has low efficiency. In this system evaporative temperature is lowered below dew point temperature. It leads to the growth of mold on the heat exchanger tubes surface or air ducts, which is also a serious problem for the depletion of ozone layer and human health. Other typical method of creating dry air is compression based dehumidification. When air gets compressed, the dew point temperature of moist air is increased till the moisture condensed from the air at a comparatively higher temperature. However, the quantity of cooling water needed for after cooling makes it unrealistic for large volume of air. It is very tough to handle the high range of pressure required with proper safety [59].

Desiccant dehumidification and air-conditioning system have received much attention in recent times as an substitute to the conventional dehumidification system. Humid air can be dehumidified without water condensation using desiccant dehumidification as there is direct contact between humid air and dry desiccant. The regeneration/reactivation of desiccant can be done using low grade regeneration heat source such as the solar energy and the waste heat from a cogeneration of other source [60,61]. Many researchers have tried to reduce the regeneration temperature by implementing high efficiency cooling sources and by utilizing high-efficiency and renewable heating sources such as solar heating [62–71].

Rotary desiccant wheel is widely applied for solid desiccant cooling and dehumidification system for removing latent load also for direct evaporative cooling by taking up sensible heat. Researchers have also developed different cycles to achieve high system performance or optimal configuration or method [72–75]. Some researchers integrated desiccant system with vapor compression cycle [76–79].

2. Desiccant dehumidification and cooling: Principle

Fig. 1 shows desiccant dehumidification and cooling system. In desiccant dehumidification and cooling system, moist air stream is allows to flow through desiccant material and then dry air comes out of the desiccant material. If the adsorption process is continued, ability to adsorb moisture of desiccant material decreases. Therefore, to keep system working constantly, the water vapor adsorbed must be removed. This is done by heating the desiccant material to its temperature of regeneration depending on the type of desiccant material used. Desiccant material can be generated by low grade heat source like solar energy, waste heat, natural gas etc.

When solid desiccant is employed, the desiccant dehumidification system consist of slowly rotating desiccant wheel of adsorbent bed. In liquid desiccant based dehumidification liquid desiccant is brought in contact with the moist air stream [80].

3. Rotary desiccant wheel

In rotary desiccant wheel, an air to air heat and mass transfer takes place, at low rotation speed. Wheel consists of a frame with thin layer of desiccant material. The channels of desiccant wheel frame are fabricated in various structures like honeycomb, triangular, sinusoidal etc. [81].

Fig. 2 illustrates the basic operating principle of rotary desiccant dehumidifier schematically. The cross section of wheel is divided into moist (process) air side and regeneration air side. When the wheel constantly rotates through two separate sections, the process air is dehumidified by the desiccant due to the adsorption effects of the desiccant material. At the same time, the regeneration air is humidified after being heated by a heater and desorbing the water from the wheel [82].

3.1. Effectiveness of desiccant wheel

Different definitions of desiccant wheel's thermal effectiveness have been introduced by different researchers. The first expression of desiccant wheel efficiency is given by Eq. (1) [83,84].

Thermal effectiveness

$$\varepsilon_{DW,1} = \frac{T_{po} - T_{pi}}{T_{ri} - T_{pi}} \quad (1)$$

T_{pi}, T_{po} and T_{ri} are inlet and outlet temperature of process air and inlet temperatures of regeneration air respectively. Another expression of regeneration effectiveness of desiccant wheel is given by Eq. (2) [83,84].

Nomenclature

D	moisture removal capacity
DD	D_{min}/D_{max}
D_{min}	minimum capacity rate (kg/s)
D_{max}	maximum capacity rate (kg/s)
D_o/D_i	diameter ratio of bed
E_{ci}	nput power of compressor (W)
EPads	adsorptive electrical power (kW)
EPr	regenerative electrical power (kW)
Hr	regeneration heat (kW)
NTU_h	number of heat transfer units
NTU_g	number of mass transfer units
ΔP	pressure drop (Pa)
Q_t	cooling capacity (W)
w	specific humidity of air
w_{ideal}	ideal specific humidity of air

Dimensionless parameter

f	adsorption to regeneration time ratio
Wr	work ratio

Greek symbols

ε	effectiveness
η	efficiency

Abbreviation

CFC	Chloro Fluoro Carbon
COP	coefficient of performance
COP_{th}	thermal coefficient of performance
COP_t	total coefficient of performance
DCHE	desiccant coated heat exchanger
DW	desiccant wheel
PSA	pressure swing adsorption
SHR	sensible heat ratio

Subscripts

car	Carnot
g	mass exchange process
h	heat exchange process

Regeneration effectiveness,

$$\varepsilon_{DW,2} = \frac{(w_{pi} - w_{po})h_{fg}}{h_4 - h_3} \tag{2}$$

where h and w is the latent heat of vaporization of water and humidity ratio respectively. The heat required to evaporate the

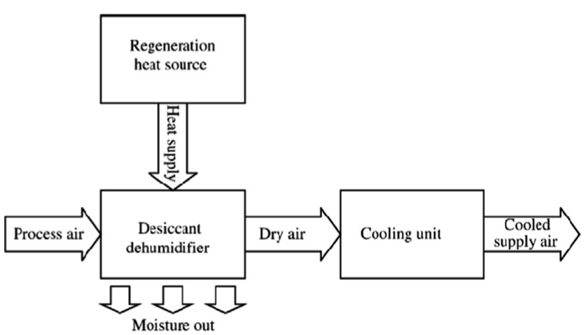

Fig. 1. Principle of desiccant cooling [80].

water adsorbed by desiccant can be calculated by Eq. (2). Above equation is applicable to both process and regeneration mass flow rate. Where different process and regeneration mass flow rates exist, the following relation (modified equation) incorporates more parameters and provides better understanding of the system effectiveness is proposed here.

$$\varepsilon_{DW,2'} = \frac{m_{process}(w_{pi} - w_{po})h_{fg}}{m_{regeneration}(h_4 - h_3)} \tag{3}$$

where, $m_{process}$ and $m_{regeneration}$ are process and regeneration mass flow rates. Van Den Bulk proposed the equation of desiccant wheel effectiveness considering the dehumidification [85]. Please see Eq. (4).

Dehumidification effectiveness,

$$\varepsilon_{DW,3} = \frac{w_{pi} - w_{po}}{w_{pi} - w_{po,ideal}} \tag{4}$$

where $w_{po,ideal}$ is the ideal specific humidity of air stream at the outlet of desiccant wheel. If its value is taken zero, one gets an ideal desiccant wheel in which air is completely dehumidified. The

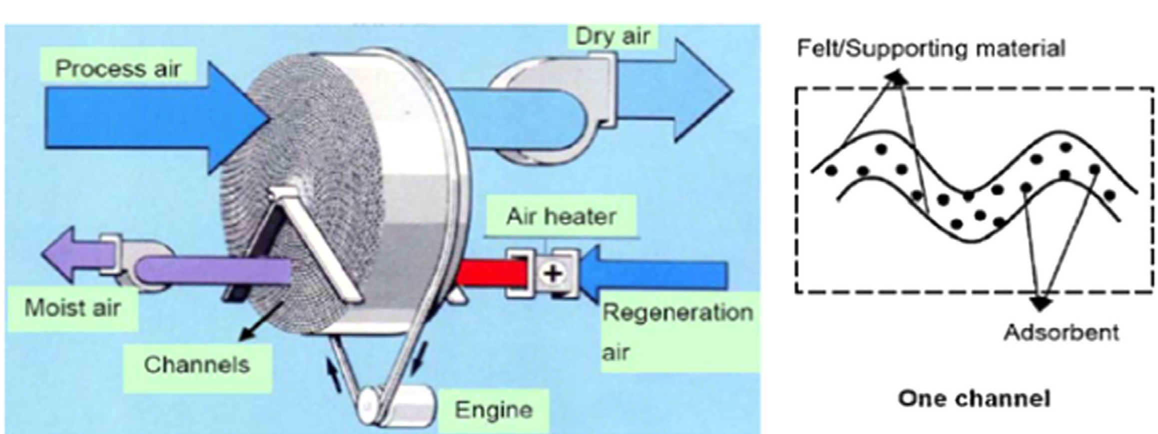

Fig. 2. Rotary desiccant dehumidifier [82].

last definition is the most useful one in the desiccant wheel optimization and is usually the objective function [86–88].

4. Characterization of desiccant wheel

Desiccative and evaporative cooling systems are based on the principle of adiabatic evaporative cooling. The maximum allowed water content of the supply air limits the extent to which the supply air can be cooled through humidification. Exclusively in hot and humid climates, the atmospheric air contains large amount of water due to which very high dehumidification rates are required. For continuous dehumidification of the process air, the water adsorbed on the desiccant material has to be driven out. This is done by permitting hot air to flow through the desiccant material i.e. regeneration [89].

Lithium chloride can attract and hold more than ten times its weight in water and is one of the most hygroscopic compounds that exist. Its ability to attract and hold water is due to the absorption of water through a chemical reaction. As lithium chloride is water soluble, precautions are needed to protect the wheel from high relative humidity. Lithium chloride prevents the growth of bacteria on the surface of wheel. It can also significantly remove the number of organisms which may be carried in the air stream. Test results show that there was typically a 25% to 50% reduction in the bacteria in air as it passes through the desiccant wheel. Lithium chloride is inert to most air stream pollutants and resistant to many contaminants such as petroleum vapor, solvents, etc.

Composite desiccant materials have been used to increase the dehumidification capacity. Different host matrices such as microporous or mesoporous silica gels, alumina, porous carbons or polymers with inorganic salts such as LiBr, $CaCl_2$, $MgCl_2$ or LiCl change the sorbent properties over a large range. A compound silica gel-haloids desiccant consisting of a host matrix with open pores (silica gel) and a hygroscopic substance (lithium chloride) was shown to have about 20–40% higher dehumidification rates compared to silica gel. Composite materials with other inorganic salt solutions such as calcium chloride were also shown to strongly increase the sorption rate and diffusion constant [90].

A molecular sieve is a crystalline material of aluminum silicate which is capable of separating molecules of different sizes by sorption. Therefore, small molecules, such as water molecules are adsorbed while large molecules pass through the desiccant wheel. Molecular sieve materials are used exclusively for the dehumidification of air to a very low level of humidity and extremely low dew points of about $-40\,°C$ to $-60\,°C$. For the same reason, the molecular sieve has a better sorption capacity at higher temperatures than other sorbents [91].

4.1. Types of molecular sieve

4.1.1. 3A molecular sieve

A 3A sieve has a pore size of 3 Å or 3 angstrom. It is not able to adsorb any molecule larger than 3 Å. Molecular sieve is an alkali metal alumino-silicate, the potassium form of the type A crystal structure. 3A molecular sieve is used primarily for removing moisture from liquefied and gaseous materials. It has become one of the most reliable desiccants for various applications [92].

4.1.2. 4A molecular sieve

A 4A molecular sieve has a pore size of 4 Å or 4 angstrom. It does not adsorb any molecule larger than 4 Å. 4 angstroms are the sodium forms of the type A crystal structure. 4A molecular sieve is primarily used for removing moisture from liquefied and gaseous materials [93].

4.1.3. 5A molecular sieve

5A molecular sieve type has a pore size that is 5 Å. It cannot adsorb any molecules smaller than 5 Å. This molecular sieve is alkali alumino silicates in the calcium form of Type A crystal structure. The basic application is separation of the normal and isomerous alkane, co-adsorption of carbon dioxide and moisture, along with pressure swing adsorption (PSA) for gases [94].

4.1.4. 13 × molecular sieve

13 × molecular sieves have a pore size of roughly 10 Å. This is considerably larger than any of the A type openings. This desiccant is used primarily for refinements of gases and liquid because it offers synchronized absorption for bi-molecule and tri-molecule. It can co-adsorb CO_2 and H_2O, H_2O and H_2S. 13 × molecular sieves also have also been applied as a desiccant for medical applications, compressor uses and as air conditioner catalyze carrier [95].

5. Solid desiccant dehumidification

5.1. Radial flow desiccant dehumidification bed

Awad et al. [96] have presented experimental and theoretical work on radial flow solid desiccant dehumidifier. The 3 mm diameter spherical particles of silica gel have been used as working desiccant in the dehumidifier for the experimental study. Investigation was done on Radial flow and cylindrical shape bed. Five experimental test units of hollow cylindrical bed with different diameters ratio were used as shown in Table 1.

The same mass of silica gel was kept constant for all units. In this study a mathematical model has been developed and compared with experimental data. Analysis of effect of bed design parameters on the desiccant bed dynamic performance shows that dehumidification period is limited to 15 minute for the diameter ratio of 7.2 for efficient operation of the hollow cylindrical bed. Maximum value of mass transfer coefficient is about 2.2 kg/m^3 was recorded.

5.2. Desiccant dehumidification with hydronic radiant cooling system for air-conditioning applications

Ameen et al. [97] have discussed the feasibility of hybrid desiccant dehumidification system combined with chilled ceiling for air-conditioning applications in humid tropical climates. This study presents a design of the hybrid system. The study also indicates definite merit of the hybrid system when the ventilation air needed for the conventional system is above a certain threshold. A trial run on the facility indicates the viability of the scheme particularly the absence of condensation of chilled panels. For a space loading of 0.1 kW/m^2, any ventilation rate above 2% for a conventional system offers opportunity downsizing chiller capacity of the hybrid system. Based on an indicative energy analysis, this hybrid system becomes more energy efficient than a conventional system when the required ventilation rate is 30% and above, as reported by the authors.

Table 1
Dimensions and weights of tested units [96].

Unit no.	D_i (cm)	D_o (cm)	L (cm)	Metal weight (kg)	Total weight (kg)	Dry silica gel weight (kg)
1	5.0	13.50	40.0	0.184	4.301	4.035
2	5.0	15.40	30.0	0.162	4.213	4.051
3	5.0	25.80	10.0	0.141	4.451	4.223
4	10.0	20.40	20.0	0.173	4.386	4.128
5	15.0	19.60	40.0	0.330	4.662	4.245

5.3. Rotary desiccant dehumidification and air conditioning

La et al. [82] have studied various desiccant air conditioning systems. These systems are free from conventional refrigerants like CFCs and use low grade thermal energy. They provide favorable humidity and temperature and are environment friendly, healthy, comfortable besides being energy saving as compared to conventional vapor compression air conditioning system. This paved way for improvement in energy utilization rate, reduction in cost and size, and standardization in design and production. These are the key issues faced by the rotary desiccant air conditioning technology for achieving more extensive application.

5.4. Heat pump-driven outdoor air processor using solid desiccant

Tu et al. [98] introduced a new outdoor air dehumidification processor using solid desiccant and combining square desiccant plates and heat pump. Each desiccant plate consists of an air channel with a honeycomb structure which is coated with desiccant material. The square desiccant plates change positions between the regenerated air duct for regeneration and processed air duct for dehumidification. The cooling capacity of the heat pump is used to cool the processed air, and the exhaust heat of the heat pump is used to provide regenerative heat to the desiccant.

5.4.1. Operating principle of the new desiccant processor

The new desiccant processor is composed of two parts: a desiccant bed system and a heat pump system. The desiccant bed system is composed of square desiccant plates, whose honeycomb structure is similar to that of a rotary desiccant wheel. There are two square desiccant plates, one each in the processed air duct and the regenerated air duct. The two desiccant plates change positions every few minutes so the wet desiccant bed can be regenerated and the dried desiccant bed can dehumidify the processed air. The processed air and regenerated air flow in their own ducts but in reverse directions. Several stages of square desiccant plates can be linked together in a line for better performance, with evaporators and condensers inserted between each plate.

The mathematical model developed for this model showed good agreement with the experimental results, with an error of less than 10%. A low regeneration temperature can be achieved with the multi-stage design. The condensing temperature of the heat pump was about 50 °C which is high enough to dehumidify the processed air from 22 g/kg to 10 g/kg with a COP greater than 4.0.

5.5. Effect of flow-duct geometry on solid desiccant dehumidification

Al-Sharqawi et al. [99] have introduced a comparative numerical solution of a conjugate-transient three-dimensional heat and mass transfer problem between silica gel as a solid desiccant and a humid transient-laminar air stream in ducts with different cross-sectional geometries like circular, square and triangular. The results show that the average velocity gradient for the triangular duct was 6.6% and 19.6% larger than that in the square and circular ducts respectively. It is also seen that the triangular duct provides the maximum convective heat and mass transfer and absorbs 11% and 42% more water than the square and circular ducts. The corresponding average pressure drop for the triangular duct was 69% and 73.5% more for the square and circular ducts.

5.6. Single bed desiccant dehumidification system

El-Samadony et al. [100] studied the dynamic performance of sealed vertical packed porous bed desiccant dehumidification system and evaluate the influence of parameter such as design and operating on the performance of the experimental unit. The system comprised (For regeneration hot air from an air heater is blown through the desiccant bed using an air blower.) one desiccant bed and three control valves. The desiccant used was Silica gel (95% white + 5% blue with an average diameter of 3.5 mm). Desiccant bed dimensions were 21 cm diameter and 90 cm height. The study shows that the desiccant bed operates as adsorber and regenerator intermittently. System performance at different conditions of inlet air and initial bed parameters show that air with inlet humidity ranging from 5.067 to 10.04 g/kg was dehumidified using silica gel to a lower level of humidity (0.7754 g/kg). Results also show that the in adsorption process ‘Rehabilitation period’ gets be eliminated if air mass flow rate is greater than 1.92 kg/h per kg of silica gel. Adsorption time was decreased with increasing air mass flow rate and inlet air regeneration temperature in the regeneration process. Uppermost adsorption rate period was achieved at high former regeneration temperature. The correlation of outlet to inlet air humidity ratio in an adsorption process obtained had an average error of 0.09 which is highly satisfactory.

5.7. Transient coupled heat and mass transfer in a radial flow desiccant packed bed

Hamed et al. [101] carried out an experimental study of the transient coupled heat and mass transfer in a radial flow desiccant packed bed. A hollow cylindrical packed bed was used as a desiccant dehumidifier as this configuration decreases the power required to blow air through the bed. Barlow model was used to predict air exit conditions from the bed and analyze adsorption and regeneration processes in the desiccant bed. This model is based on simple effectiveness equations for steady state heat and mass exchangers within a finite difference procedure. Result obtained at different conditions of temperature and humidity of air entering the regenerated bed shows that the initial water content of the bed and its initial temperature are the most effective parameters which influence the system performance. It was observed that bed cooling during adsorption improves system performance.

The effectiveness of the mass and heat exchange process and COP was obtained using Eqs. (5)–(7).

$$\epsilon_g = \frac{1 - e^{[-NTU_g(1-DD)]}}{1 - DD.e^{[-NTU_g(1-DD)]}} \tag{5}$$

where, ϵ_g is the effectiveness of mass exchange process.

$$\epsilon_h = \frac{1 - e^{-[NTUh(1-CC)]}}{1 - CC.e^{[-NTUh(1-CC)]}} \tag{6}$$

where ϵ_h is the effectiveness of heat exchange process.

The system COP is defined as

$$\mathrm{COP} = f * \left(\frac{\mathrm{Coolingcapacity}}{H_r.\eta_{car} + \mathrm{EP_{ads}} * f * \mathrm{EP}_r} \right) \tag{7}$$

Simple effectiveness equations for steady state heat and mass exchangers within a finite difference procedure are applied for the simulation of coupled heat and mass transfer in adiabatic desiccant bed. Comparison between theoretical and experimental data showed acceptable agreement in most conditions. It is noted that regeneration period as well as regeneration temperature play a decisive role in the subsequent adsorption process. The performance of the system can be enhanced by increasing the pre-cooling period. Also, bed cooling during operation using suitable method enhances the performance. It has been found that COP decreases with time during adsorption.

5.8. A self-cooled solid desiccant cooling system based on desiccant coated heat exchanger

Dai et al. [102] invented a new technology of self-cooled solid desiccant cooling system (SCDHE) by integrating desiccant coated heat exchanger (DCHE) and regenerative evaporative cooler. To produce chilled water, regenerative evaporative cooler was adopted in the system. Water was pumped again into desiccant coated heat exchanger to realize self-cooled dehumidification. Similarly, hot water was used in regeneration process to regenerate the desiccant material. A mathematical model was developed to validate the feasibility and to analyze performance of this novel system as well as understanding the effects of ambient air condition. It was found that this system is feasible and provides satisfactory supply of air to the room under simulated ARI summer conditions. The required regeneration temperature was found to range between 50 °C and 80 °C which was lower than rotary wheel desiccant cooling system. Also, there exists an optimal switch time and suitable control mode for system to obtain enhanced performance in terms of cooling power. It is observed that SCDHE system provides satisfactory level of air supply which conventional DCHE cooling system without regenerative evaporative cooling system can not . It also results in increased cooling power. Cooling power of SCDHE system increased by about 30% under simulated conditions compared with conventional DCHE cooling system. The author developed a coupled heat and mass transfer mathematical model of SCDHE system by linking different component models to validate system feasibility and investigate system performance. The system is an internal feedback cycle. Parametric hypothesis computation mode, instead of conventional sequencing computation, was adopted in simulation process. The system performance in terms of outlet air state and cooling power was predicted. It was observed that performance of SCDHE system does not vary greatly with ambient temperature under simulation condition. However, both can handle latent load. Cooling power of the system increased under high humid condition which demonstrates that the system can operate under humid conditions.

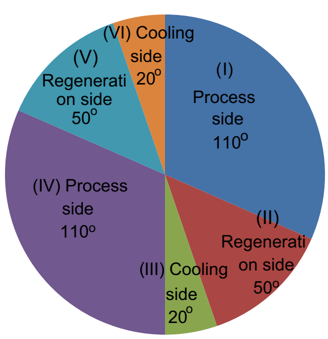

Fig. 3. Cross section area of one rotor six stage desiccant wheel [103].

5.9. Solar energy assisted hybrid air conditioning system, with one-rotor six-stage rotary desiccant cooling system

Elzahzby et al. [103] developed solar energy assisted hybrid air conditioning system with one-rotor six-stage rotary desiccant cooling system. There exists one process air path, two regeneration air paths, and two cooling paths all of are realize by only one wheel. Desiccant wheel was divided into 6 parts as shown in Fig. 3. Author has presented a mathematical model for predicting the performance of solar energy assisted hybrid air conditioning system. In this work honeycombed silica gel desiccant wheel was used with three air streams. The mathematical model was validated with the experimental data. The range of regeneration air inlet temperature was changed from 65 to 140 °C while area ratio of process air to regeneration air was changed from 1 to 3.57 and regeneration air inlet velocity from 1.5 to 5.5 m/s. These were examined for a range of rotation speed from 6 to 20 revolution/h. The optimization of these parameters was conducted based on the moisture removal capacity *D*, relative moisture removal capacity, dehumidification coefficient of performance and thermal coefficient of performance. The model was adopted to investigate the influence of the main parameters on system performance and optimal rotation speed by increasing the regeneration air inlet temperature, the moisture removal capacity, DCOP and COP_{th} increases. The optimal rotation speed increased with increasing inlet temperature of the regeneration air. Moisture removal capacity *D* and relative moisture removal capacity increased with increasing regeneration air inlet velocity in the range 1.5 m/s to 3.5 m/s. When the regeneration air inlet velocity was changed further from 3.5 m/s to 5.5 m/s, the increase of moisture removal was not found significant. With increase in the area ratio of process to regeneration air, the moisture removal capacity decreased as well as the DCOP and COP_{th} increased. At different regeneration air inlet velocities, the dehumidification desiccant wheel performance decreased with increasing the wheel rotation speed. Moreover, the optimal rotation speed increased with increasing regeneration air inlet velocity (Fig. 4).

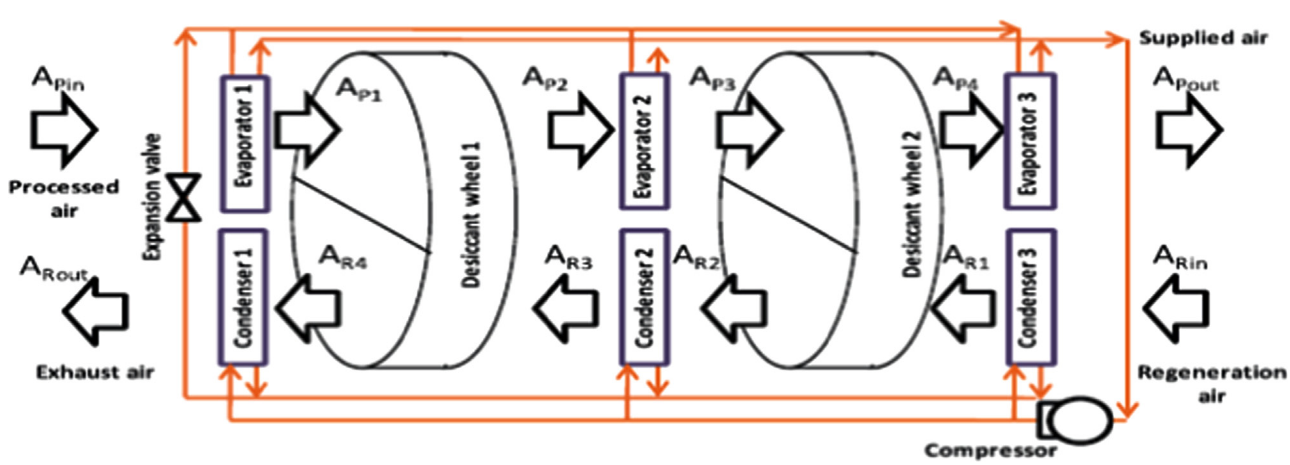

Fig. 4. Heat pump driven two stage desiccant wheel cooling system [104].

5.10. Two-stage desiccant dehumidification cooling system

5.10.1. Two-stage desiccant cooling system

Rang et al. [104] developed the heat pump-driven two-stage desiccant wheel system in which evaporators were used as cooling medium and condensers were used as heating medium. Models of the desiccant wheel and heat pump systems were utilized to predict system performance. The effects on system performance of the compressor power input, the heat exchange area distribution between evaporators and condensers, the wheel's rotation speed, and the inlet parameters of the processed air were investigated. The total coefficient of performance of this system (COP_t) is calculated by dividing the cooling capacity of the processed air (Q_t) by the power input of the compressor (E_c), as shown in Eq. (8).

$$COP_t = \frac{Q_t}{E_c} \tag{8}$$

The supplied air humidity ratio of 10 g/kg, resulted in 5.5 COP_t of the desiccant system under Beijing summer condition. The key to improving system performance is to match the cooling capacity and exhaust heat provided by the heat pump with the requirements of dehumidification and regeneration. An improved system utilizing an indirect cooler to recover the cooling capacity from the indoor exhaust air was proposed COP_t. Improvement of 15% was observed when compared to the original system. For desiccant wheels, there exists an optimal rotation speed. The thicker the wheel, the smaller was the optimal rotation speed. The optimal rotation speeds were 10 revolution/h and 20 revolution/h when the wheel thickness was 0.15 m and 0.1 m, respectively. Thus, the main way to improve system performance is to match the cooling capacity and exhaust heat provided by the heat pump with the requirements of the desiccant wheel. An improved system utilizing an indirect cooler to recover the cooling capacity from the indoor exhaust air was then proposed. Keeping same moisture system, COP_t of the improved system increased from 5.5 to 6.3, a 15% improvement ratio in Beijing summer outdoor conditions, as compared to the original system

5.10.2. Desiccant dehumidification system with two-stage evaporative cooling

Hourani et al. [105] developed a two-stage evaporative cooling system hybrid air conditioning that uses 100% fresh air to optimize the system operation with respect to energy and water consumption while maintaining occupant thermal comfort. The two-stage evaporative cooling system is shown in Fig. 5. The first stage consisted of cooling a fraction of the dehumidified air stream using an evaporative cooling pad, mixing the cooled air with the remaining bypassed air fraction and then supplying it to the space in order to minimize water consumption and limit the indoor relative humidity to acceptable levels. The second stage consisted of locally cooling the occupant's microclimate using a personalized evaporative cooler (PEC) that will allowed for higher room bulk air temperatures. The system was implemented in an office space in Beirut and the optimization was carried using a derivative free genetic algorithm that handled three variables: the regeneration temperature, the air mass flow rate, and the fraction of air entering the evaporative cooler. The two-stage system achieved a 16.15% reduction in energy consumption and a 26.93% reduction in water consumption compared to a single-stage evaporative cooling system for the same thermal comfort level where the reduction in the space's relative humidity due to the operation of the two-stage system ranged between 4.33% and 11.55%. Finally, personalized cooling allowed the occupants to individually control their thermal comfort level rather than having the entire space fixed at a low set point temperature.

5.10.3. Two-stage air dehumidification system for the tropics

Safizadeh et al. [1] studied two stage air dehumidification systems for tropics. Fig. 6 shows a two-stage solar assisted dehumidification system. This system consists of an efficient chiller unit and active chilled beams integrated with a sensible cooling system. Commercially available standard solid desiccant dehumidification systems are generally rotor based systems in which the solid desiccant material was impregnated on a rotary wheel. Stationary desiccant systems comprising two adsorption units were also designed. These solid desiccant systems have the limitation of an increased temperature during the dehumidification process. In order to compensate for this effect, an indirect evaporative cooling unit was proposed. The cooling unit was installed after the rotary desiccant dehumidification system as a separate unit in order to cool down the warm dehumidified supply air. Although the supply air temperature is reduced considerably by this evaporative cooling unit, the adsorption efficiency of the desiccant bed is still low due to high desiccant bed temperature. To overcome this problem, SERIS in collaboration with Fraunhofer-ISE, developed evaporative cooling and adsorption process in a single unit called "Evaporative cooled sorptive dehumidifier (ECOS)". The experimental analysis showed that the ECOS unit can dehumidify the ambient air in order of 4–6 g moisture per kg of dry air under warm and humid climate conditions of Singapore. In

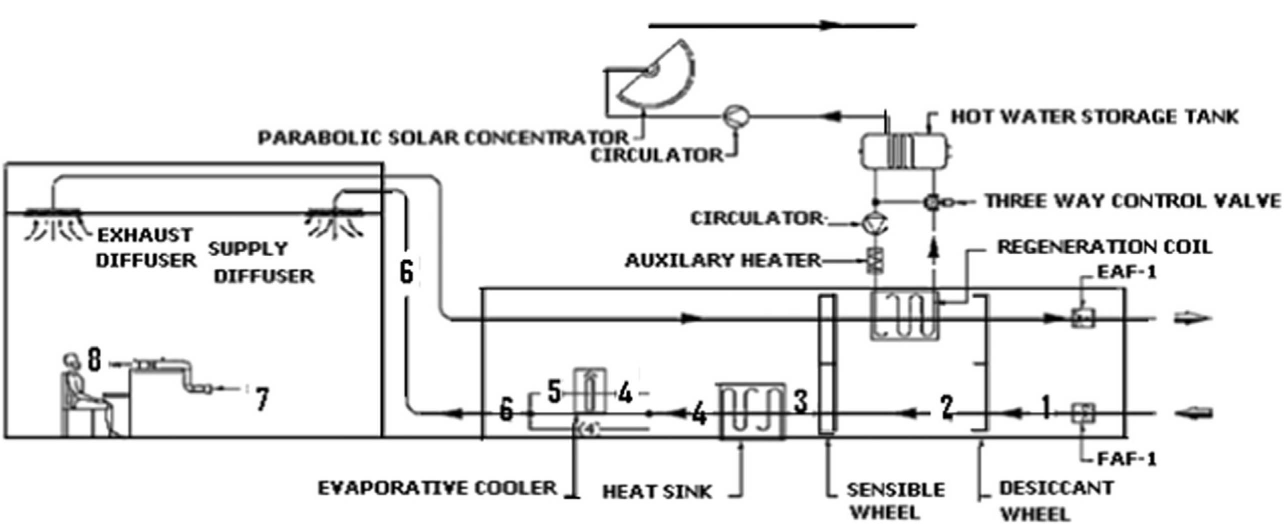

Fig. 5. Desiccant dehumidification system with two-stage evaporative cooling [105].

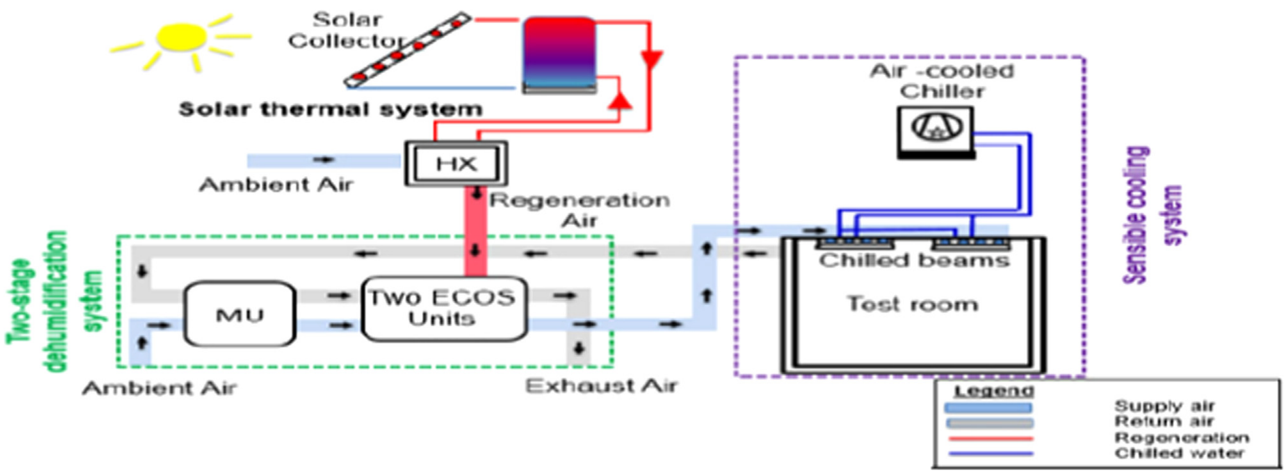

Fig. 6. Solar-assisted air-conditioning system installed at SERIS [1].

order to enhance the dehumidification performance, a pre-dehumidification system was introduced. Additional dehumidification is performed by a membrane based-dehumidification system that demands almost no electric energy except for air transport. The main purpose of this research work was to evaluate the performance of the two-stage dehumidification system including the membrane and ECOS units for different operating parameters such as air flow rates and regeneration temperatures under warm and humid climate conditions. These analyses provide valuable information on the development of air-dehumidification systems for practical application in the tropics. The two-stage dehumidification system can dehumidify ambient air in the order of 8–10 g_v/kg_{air}. The optimal COP as high as 0.6 was found under the following conditions: air flow rate: 200 m^3/h and regeneration temperature: 65 °C. The COP may be higher for other operating conditions and other design and/or material parameters of the two dehumidification sub-units. The dehumidification performance of the membrane unit improved due to lowering of the ambient and return air flow rate. The dehumidification performance of the ECOS unit get elevated by increasing the air flow rate and the regeneration air temperature. The removed energy of the ECOS unit increases with the increase of the air flow rate and decreases slightly by rising regeneration air temperature.

6. Regeneration of solid desiccant

6.1. Regeneration of silica gel desiccant by air from a solar heater with a compound parabolic concentrator

Pramuang et al. [106] have developed a system for the regeneration of silica gel desiccant by a solar air heater for use in an air-conditioning system has been investigated. The hot air was produced by a compound parabolic concentrator (CPC), which has an aperture and receiver areas 1.44 and 0.48 m^2 respectively. The regeneration temperature was started at 40 °C. The regeneration rate and the regeneration efficiency were greatly affected by the solar radiation, but depended only slightly on the different initial moisture contents of silica gel and the number of silica gel beds. The regeneration of silica gel provided by the CPC collector is suitable for a tropical climate where the diffused solar radiation is high throughout the year. Overall dimension of each collector has 0.6 m height, 0.6 m width, and 1.2 m length. The receiving surface, which was painted non-selective matt black, forms the upper side of a rectangular air flow duct of depth 0.03 m made of aluminum sheet 0.2 mm thick. The bottom of the duct was insulated with fiber glass 50 mm thick. The optical efficiency and heat loss of the collector was 0.68 and 8.51 W/m^2 K. A hot wire anemometer was used to measure the air speed v. Constant flow was maintained by controlling the valve of air blower. It was found that during the period 09:00–16:00 the average regeneration rate under various weather conditions was 0.19 kg/h per square meter of aperture area. The highest regeneration rate found was 0.51 kg/h in one silica gel bed with air flow rate 0.007 kg/s. It is concluded that the CPC collector producing temperatures up to 80 °C could be used to regenerate silica gel in 2 h around solar noon. Concluding, a truncated CPC air heater with concentration ratio 3 is capable of giving outlet air temperatures 10 °C above ambient temperature on a cloudy day, and 50 °C above ambient on sunny days. This air can be used to regenerate silica gel desiccant for air conditioning in tropical humid climates.

6.2. Regeneration of solid desiccants by evacuated tube solar air collector

Yadav et al. [107] experimentally investigated the rates of regeneration of various solid desiccants like silica gel, activated charcoal and activated alumina. The main objective of this experimentation was to analyze the feasibility of regeneration of these desiccants using evacuated tube solar air collector. The performance of evacuated tube solar air collector was investigated. This evacuated tube solar air collector was used to regenerate various desiccants at various flow rates of air. Experimental comparison between various types of desiccants in terms of dehumidification performance was analyzed according to Indian climatic conditions.

The experiments were aimed at investigating the regeneration rates of silica gel, activated charcoal and activated alumina. Since some level of moisture content should be present in the desiccants, these desiccants were exposed to humid air over the night. The adsorption process was carried out immediately after regeneration process in the evening time.

In this setup, container was integrated with evacuated tube solar air collector. The evacuated tube solar air collector produced hot air for regeneration of various desiccants which were present in the container. In this setup, regeneration of desiccant occurred in day time, and adsorption occurred in evening time.

In this experimental investigation, the air needed for regeneration was heated in an evacuated tube solar collector with a surface area of 4.44 m^2. The desiccants were regenerated at temperatures in the range of 54.3–68.3 °C. The regeneration performance was greatly influenced by the regeneration temperature

Table 2
Comparative study of solid desiccant dehumidification/cooling/air-conditioning system.

Reference	Year of work	Work carried out	Type of work	Desiccant used	Type of system	Regeneration source
Rush et al. [109]	1975	MEC field test installation using solar energy- description	Experimental	Silica gel	Single stage	Solar energy, natural gas
Joudi et al. [110]	1987	Desiccant-evaporative air-conditioning system using solar energy	Experimental	Silica gel	Single stage	Solar energy
San et al. [111]	1994	Silica gel packed-bed system-Modeling and testing	Experimental	Silica gel	Two stage	Solar energy
Singh et al. [112]	1998	Silica gel regeneration in multi-shelf regenerator	Experimental	Silica gel	Single stage	Solar energy
Techajunta et al. [113]	1999	Air dehumidification and air-conditioning in a tropical humid climate using solar energy- experimental investigation	Experimental	Silica gel	Single stage	Solar energy
Zhuo et al. [114]	2006	Desiccant air conditioning using solar energy- experimental investigation and system design	Experimental	Composite silica gel	Single stage	Solar energy
Kabeel [115]	2007	Rotary desiccant wheel (honeycomb matrix) air conditioning using solar energy	Experimental	Calcium chloride	Single stage	Solar assisted
Yilmaz et al. [116]	2010	Two stage novel desiccant cooling system -Experimental investigation	Experimental	Silica gel	Two stage	Electric heater
Ge et al. [117]	2008	Desiccant cooling using one rotor two stage rotary system- Experimental investigation	Experimental		One-rotor two stage	Solar energy
Ge et al. [118]	2010	Comparison of Solar powered rotary desiccant and conventional vapor compression cooling system – desiccant cooling Performance study	Experimental	Silica gel and lithium chloride	Two stage	Solar energy
Angrisani et al. [119]	2015	Comparison of hybrid desiccant cooling and other air-conditioning technology – Experimental assessment	Experimental	Silica gel	Single stage	Thermal waste of the cogeneration and by natural gas boiler

but depended on the initial moisture content, temperature of the desiccants, and flow rate of regeneration air. Comparison of the performances showed that at high hot air flow rate the regeneration time and adsorption time were shorter for these desiccants than that at low flow rate. Silica gel was observed to perform better at high as well as low flow rates for regeneration and adsorption than activated alumina and activated charcoal.

6.3. *Electro-osmotic regeneration of solid desiccant*

Qi et al. [108] investigated experimentally the performance and possibility of a novel electro-osmotic regeneration method for the solid desiccant system. This could adsorb moisture from the wet air and regenerate the electro-osmotic force at the same time. The zeolite powder with both adsorptive and electro-osmotic characteristics was used to fabricate the solid desiccant. The quantity of the removed moisture was measured with and without application electric field to validate the possibility of the electro-osmotic regeneration. The maximum water removal rate per electric strength gained was $1.1{*}10^{-7}\ \mathrm{kg\ m^{-1}\ s^{-1}\ V^{-1}}$. The test data showed that there was an obvious electro-osmotic regeneration effect in the experiments. The whole electro-osmosis process was divided into three phases because of the Joule heating effect and electrode corrosion. It restricted the performance of the experimental system. In particular, a filter cloth under the cathode made a superior electro-osmotic regeneration effect than without the cloth. The experimental results illustrate that the system has the potential of energy-saving and low regeneration temperature. The electro-osmotic regeneration method then seems to be potential regeneration method for the solid desiccant system. Further work is needed for designing an improved electro-osmotic regeneration system that results in better performance and lower power consumption. Use of corrosion-resistant electrode or introducing several new measures such as interrupted power is suggested.

Table 2 shows the comparative study of solid desiccant dehumidification/cooling/air-conditioning system.

7. Conclusion

In the present paper, an attempt has been made to review different desiccant and regeneration methods. Desiccant dehumidification is an established and successful technology used for many years. However, decreasing the cost of desiccant dehumidification systems and improving their performance will definitely provide more opportunities for desiccant dehumidification technology. Desiccant dehumidification systems in near future are likely to solve the challenges facing the HVAC industry. Increased ventilation rates, need for improved indoor air quality, better humidity controls and phasing out of CFCs has recommitted developing national standards as better as to achieve higher efficiency for cooling systems and lower peak electric demands. These factors and the ability for desiccant systems to solve specific problems are driving these desiccant technologies to the main stream of the air-conditioning market.

The state of the art technologies reveal that it is now possible to select right desiccant materials, desiccant wheel geometry and method of dehumidification and regeneration.

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