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A comprehensive review on solid desiccant-assisted novel dehumidification and its advanced regeneration methods

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Abstract
A solid desiccant-based novel dehumidification technique in indoor cooling is a viable substitute for a traditional dehumidification system in regions with high humidity levels. The ozone layer is being steadily destroyed by vapour compression-based conventional dehumidification systems, which also have a number of other disadvantages such as excessive power consumption and a rise in the amount of chlorofluorocarbons type refrigerant leakage in the atmosphere. As compared to traditionally used vapour compression type refrigeration air conditioners, solid desiccant-integrated novel cooling may be more advantageous as it provides more easily accessible, cost-effective, and ecologically sound cooling. It can be more competitive when it is reactivated by freely available renewable heat available from solar power and industrial waste heat. Not only marginally saving energy, but it can also help in drastically lower operational costs. Recently, many studies have been carried out with aim of ameliorating desiccant air conditioners' overall performance through the development of novel system configurations, enhanced system designs and better controls, and the integration of hybrid energy sources for desiccant reactivation as well as sub-systems technological advancements. By this means, the present study offers a thorough analysis of the previously described investigations. This offers detailed study on possible suggestions and recommendations for possible future work direction based on the most recent investigations in the field of the desiccant-powered novel cooling techniques. These recommendations can help to amplify the efforts to find better solutions to concurrent technological issues, which will definitely ameliorate the overall performance of desiccant-integrated dehumidification and hybrid cooling in the field of heating, ventilation and air conditioning.

Keywords Dehumidification · Desiccant-integrated cooling · Regeneration heat · Renewable solar energy · Waste heat

List of symbols

C_p	Specific heat capacity, kJ kg℃$^{-1}$
T_{db}	Dry bulb temperature of air, ℃
T_{wb}	Wet bulb temperature of air, ℃
ΔH	Specific cooling capacity, kJ kg^{-1}
h_1	Enthalpy of air at outdoor condition, kJ kg^{-1}
h_2	Enthalpy of air after passing through dehumidifier, kJ kg^{-1}
MPS	Moisture removal capacity of process air during dehumidification, gh^{-1}
MRS	Moisture addition to air by reactivation process during reactivation, gh^{-1}
m_1	Air flow rate in adsorption sector of process air flow, gkg^{-1}
m_2	Air flow rate in reactivation sector of reactivation air flow, gkg^{-1}
w_1	Specific humidity of air at outdoor condition, gkg^{-1}
w_2	Specific humidity of air after passing through dehumidifier, gkg^{-1}
COP	Coefficient of performance
DEC	Direct evaporative cooler
IEC	Indirect evaporative cooling
DW	Desiccant dehumidifier wheel
d	Desiccant
EC	Evaporative cooling
HRW	Air-to-air heat recovery wheel
HVAC	Heating, ventilation and air conditioning

Greek letters

ω	Relative humidity
ε	Dehumidifier effectiveness

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Introduction

In present days, the world is suffer from energy crises especially in the field of sustainable energy use, for producing indoor cooling and comfort for the hot and humid climatic zones where control of humidity is almost important in addition to temperature control for the cooling. Conventionally used vapour compression-based cooling system typically used hydrochlorofluorocarbons (HCFCs) or chlorofluorocarbons (CFCs) which are mainly responsible for slow depletion of surrounded ozone layer over earth which protecting it from UV rays. Due to increased demand for indoor cooling led to a significant increase in power consumption, as the high moisture level in ambient and indoor space especially in tropical countries. Dry air is crucial for increasing product durability since it is used in many important industries, such as the manufacture of industrial chemicals, food and pharmaceuticals, among others, to require dry indoor with minimum moisture level and also the demand from the storage of perishable goods, inorganic objects, biological plants and hygroscopic raw materials [1].

In order to remove the latent heat component of the room cooling load, the traditional refrigerant vapour compression system (VCS) cools the process air down below its dew point (sometimes very low temperature 3–5 °C) in order to condense out water vapour contained therein to dehumidify the supply process air. This sometimes resulted to overcooling and so require further reheat it to meet design supply conditions which does not make sustainable energy use. If the latent load is handled by other means than by this deep cooling, two components of the burden on the conditioner, brought about by the presence of latent load, will be avoided. Those are, namely, (1) the energy required to bring the air from the supply temperature down to the temperature of condensation of water vapour contained in the process air (below the dew point of the air), and (2) the energy needed to reheat the air from that temperature up to the supply air temperature. When the sensible heat ratio (SHR) of the conditioned space is low, the sum of these two components increases dramatically. Furthermore, the VCS is actuated by electricity, the generation of which involves most often the utilization of fossil-fuelled power plant with the consequent emissions of carbon dioxide (CO_2) into the atmosphere. Finally, the refrigerants used in this air-conditioning technology are more or less CFCs based ones, that many countries are taking steps to phase out or are considering doing so. The desiccant cooling as control temperature and humidity separately will able to put off the dehumidifier or cooling coil operation as per requirement separately when concern criteria of weather humidity or cooling control can be achieved. This saves lot of energy for operating the same. More importantly, when desiccant cooling systems powered by free energy sources such as solar energy, and waste heat for desiccant wheel regeneration, it can significantly reduce the operating costs and increase considerably the accessibility to the air conditioning for the populations in remote areas, especially in developing countries. Merits of liquid-type desiccants were to produce less pressure drop and remove some pollution from the air while adsorption and desorption of moist air. The merits of solid-type desiccant cooling system over traditional system like improved air quality in interiors, less electric consumption while using alternative renewable free energy sources for desiccant regeneration. In context to limitations of desiccant cooling, carryover of liquid desiccant with the process/regeneration air is a disadvantage of these systems. Corrosion and crystallization are other common problems for the liquid desiccant systems. Slightly high initial cost to set up the desiccant cooling system is also the limitation of this cooling system. Thus, the desiccant cooling can be a viable option to the traditional vapour compression air-conditioning technology to attenuate the effects of its drawbacks, or an alternative to it for assuring more accessible, economical and cleaner air conditioning. The purpose of an integration of desiccant-assisted dehumidification to other HVAC systems such as DX system, VRC system and chilled water cooling is to reduce its size and enhance its coefficient of performance. Because the latent load is handled independently by the desiccant dehumidifier, the need of cooling the ventilation air below its dew point is obviated. The temperature of evaporation can thus be lifted up to 15 °C from its generally practiced level of 5 °C for the traditional cooling systems. The increase in evaporation temperature will entail the increase in the system's coefficient of performance (COP). This assemblage can be useful in humid climates where the wet bulb temperature is fairly high. In such climates, a significantly downsized cooling unit can be supplemented with a desiccant-assisted hybrid cooling order to reach the desired indoor temperature, thus enabling costs and energy savings and improving the indoor air quality.

An innovative kind of air conditioning called desiccant cooling aids in resolving problems with the environment and the economy brought on by the usage of traditional vapour compression air-conditioning systems. If dehumidification is accomplished using freely available renewable free energy sources rather than use of high-grade electrical power to minimize moisture during cooling that requires less energy as compared to conventional air conditioners [2]. Solid-based desiccant-powered innovative HVAC systems are an intriguing better option to electrically powered vapour compression cooling systems [3–11]. By delivering industrial waste energy [12] and freely available renewable energy [8, 13], which are good source for primary energy, the need for heat for desiccant reactivation may be supplied from this viable energy sources. By making the best use of solar heat or waste industrial energy in the form of primary energy, the desiccant-integrated dehumidification and innovative hybrid cooling system maintains required interior comfort. Desiccant wheel integrated conventionally used evaporative cooling or vapour compression system can effectively handle indoor moisture level for required thermal comfort as per design conditions demanded. In this type of hybrid configuration, rotary desiccant dehumidifier effectively controls the humidity of moist supplied air while sensible cooling maintains temperature to meet required thermal comfort. With this novel configuration, the need for a sensible cooling coil for an evaporator to operate below its dew point temperature and post reheating (in case of over cooling) is eliminated. Additionally, it prevents moisture condensation, which is an inevitable issue when the surrounding air is too moist. In addition to effective humidity control, hybrid configuration may significantly save operating costs and demand for high-grade electrical power. By this way both energy and money savings in moist climate by separate temperature and moisture control, desiccant cooling was, therefore, proposed as a viable option to traditional VCR air conditioners or evaporative cooling.

The main objective behind carrying out this review is to summarize key findings of solid desiccant-powered dehumidification and cooling systems in tropical climates. Additionally, it demonstrates the recent advancements in solid desiccant cooling system research and provides details on future applications. It also includes a quick comparison of the performance of several systems with varied operational settings and environmental conditions. The article is divided into categories based on the cooling option, viable reactivation energy provision and system configuration for hybrid mode operation. Coupling dedicated desiccant dehumidification system with traditional VCR cooling resulted to hybrid system which is highly effective in individual moisture and temperature control to ameliorate energy saving for its typical use. To obtain better performance of by the use of hybrid configuration, researchers have also created several cycles [14–17]. A dedicated desiccant dehumidification system and a traditionally used vapour compression cycle or sensible evaporative cooling was combined by certain researchers in many cases [18–21].

Materials known as sorbents are those that draw and retain certain vapour or liquid fluids. If a chemical change happens, the process is called adsorption; if not, it is called absorption. Among the sorbents that persist a strong affinity for moisture present in the air are commonly known as desiccants, which can be found in both liquid and solid forms. By nature, the desiccant material is a hygroscopic substance which attracts water molecules from humid air as vapour pressure of mixture changes. A solid desiccant's large surface area under dry conditions can adsorb and hold water molecules whereas liquid desiccants absorb water molecules as per its individual configurations.

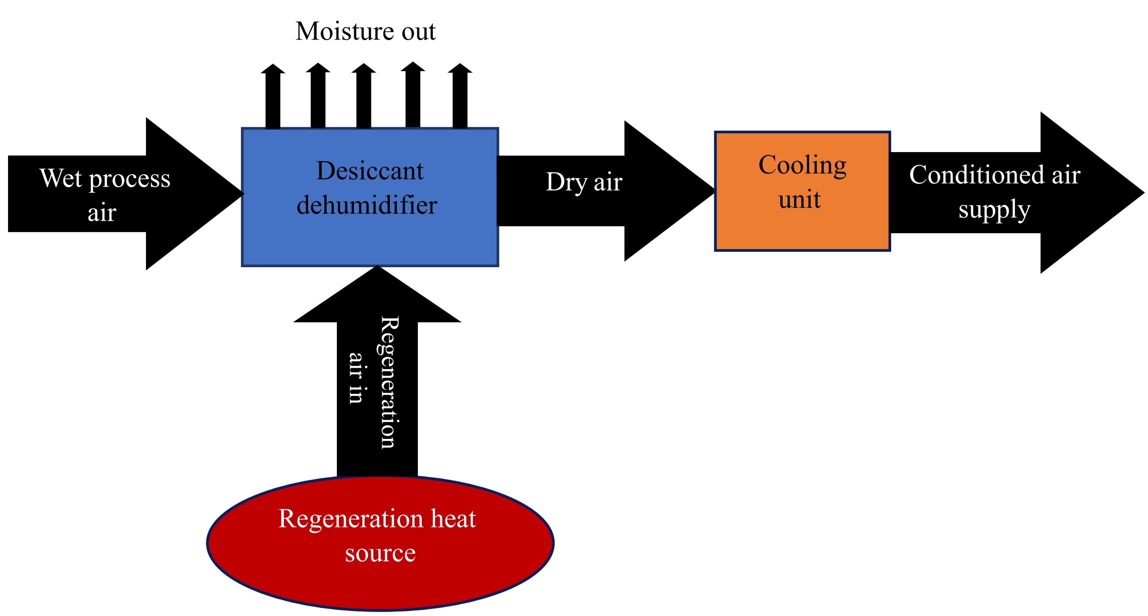


Fig. 1 Principal of desiccant-based dehumidification and innovative cooling system

Overview of cooling with solid desiccant

Outline of solid desiccant cooling

Various experts have conducted several investigations on desiccant-assisted dehumidification-based innovative cooling systems earlier. An integration of rotary dehumidifier with an evaporative cooler and a regeneration heat source, Pennington [22] suggested an initial cooling cycle basically works on principle of desiccant cooling HVAC. After that, Dunkle [23] also proposed a cycle similar to this one that used a molecular sieve's dehumidifier [24] along with a supplementary heat exchanger. The industry-based desiccant technology was initially developed by Shelpuk and Hooker [25] as the US mission for solar-based renewable energy mission [26]. In their study, the fundamental concept about working of desiccant-integrated dehumidifier [27] for the open-cycle adsorption cooling for an industrial use by the use of renewable solar energy has been revealed an experimental effort. According to Sheridan et al. [28], solid desiccant cooling systems have experimentally proven more efficient than traditional cooling cycles. The dehumidifier wheel is the prima component in the performance evaluation of a solid desiccant dehumidification-based innovative air-conditioning system, according to Farooq and Ruthven [29]. It has been experimentally proven that by increasing the dehumidifier wheel's performance can increase overall performance of hybrid cooling system. Jain et al. [30] simulated performance of the four different cooling cycles based on different desiccant air-conditioning configurations for several Indian towns. In different climatic zones, they found that the Dunkle cycle performed better than the recirculation and ventilation cycles in maintaining required

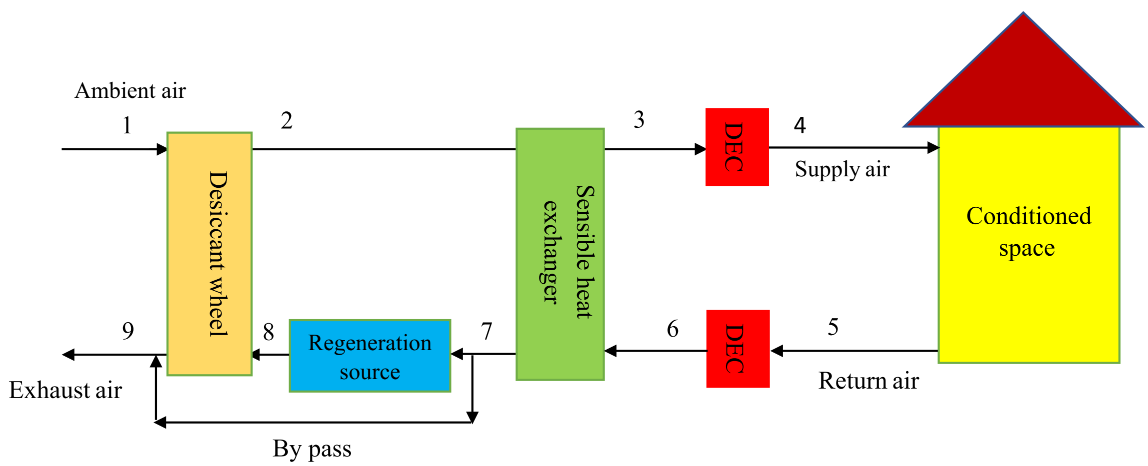


Fig. 2 Pennington cycle

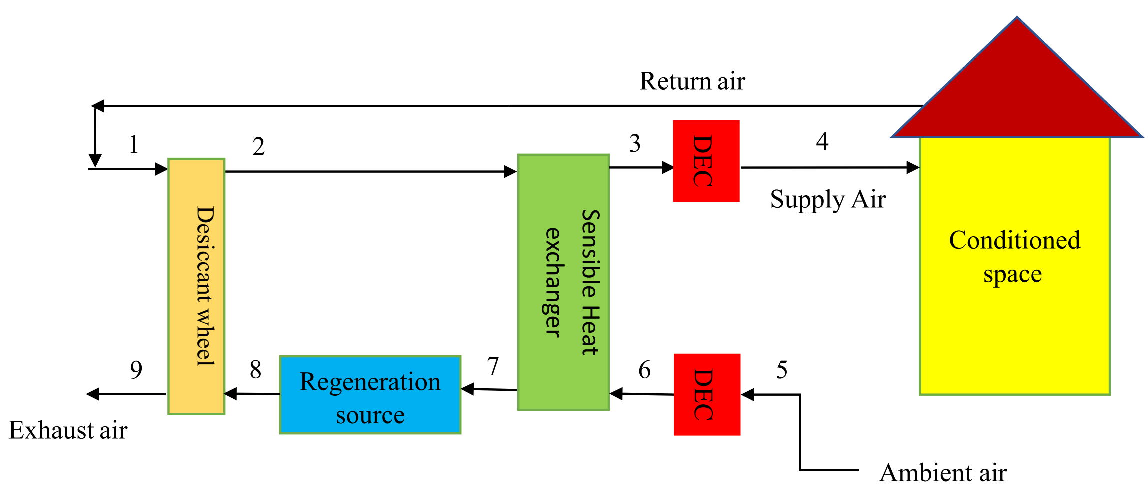


Fig. 3 Recirculation cycle

indoor comfort. An experimental evaluation of an indirect evaporative cooler used in combination of the desiccant dehumidification-integrated innovative cooling system was summarized by Belding and Delmas [31]. Using a novel rotating honeycomb wheel for the desorption and adsorption processes, Kabeel [32] claimed minimum energy required for working of a solar-powered desiccant-assisted dehumidification and innovative hybrid cooling system under various ambient conditions. Parmar et al. [33] analysed different configurations of an evaporative cooling integrated to the desiccant dehumidifier in different climatic zones to determine the climatic applicability of this hybrid cooling cycles.

Principles of working of solid desiccant-assisted innovative cooling

Solid desiccant-powered hybrid cooling unit consists of mainly three critical components, namely rotary desiccant wheel, reactivation thermal unit and a sensible cooler. The desiccant wheel having matrix which can be laden with the thin layer of desiccant material to form the fine flutes. When humid air passes through the flute, the moisture content mainly adsorbed by the dry desiccant surface as difference in vapour pressure among moist air is higher as compared to the desiccant material. This resulted to the dehumidified warm air at the desiccant wheel exit. Its temperature is lowered further as per indoor supply design conditions by passing it over sensible cooling coil. For to work it in cycle, regeneration heater is provided to reactivate the desiccant

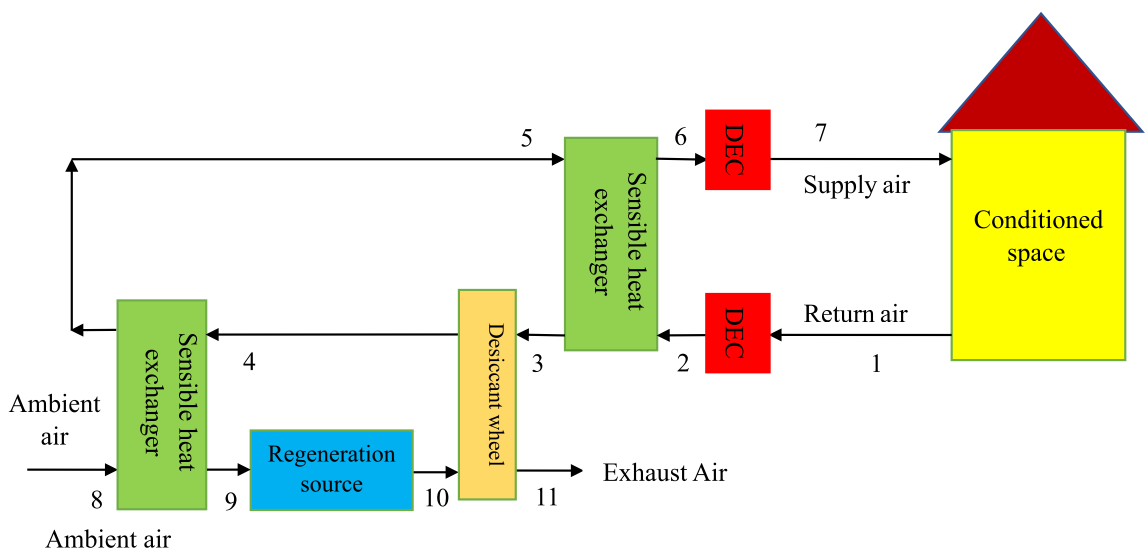


Fig. 4 Dunkle cycle

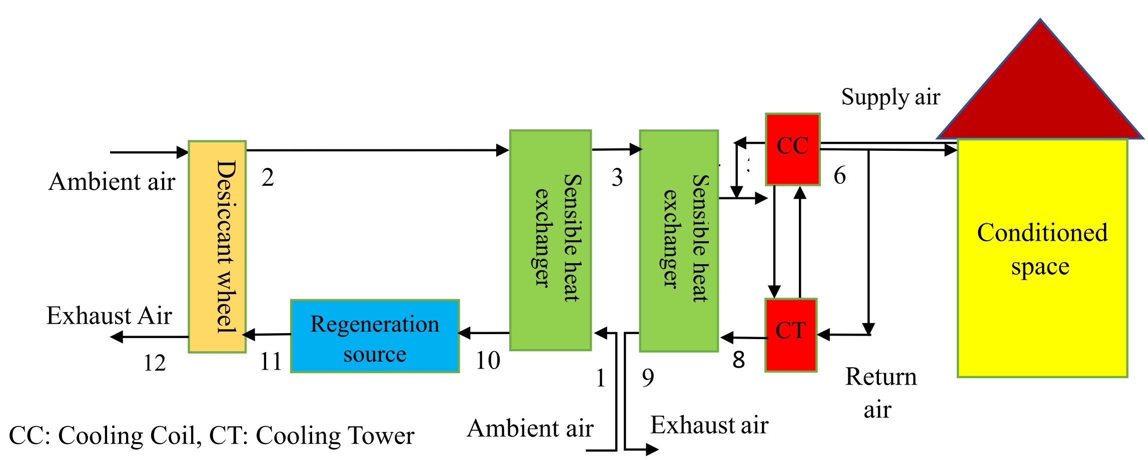


Fig. 5 SENS cycle

surface to extract out moisture from it. Desiccant material used in dehumidifier can be reactivated by variable energy sources include renewable primary energy like as solar heat or waste heat available in industrial cogeneration processes. As per the type of sorptive material used in construction of rotary desiccant dehumidifier, we may classify them as solid desiccant or liquid desiccant [34].

Desiccant cooling and dehumidification: concept

A desiccant-assisted dehumidification and innovative air-conditioning unit layout is depicted in Fig. 1. The sorptive desiccant is the material that is very soluble in water and hygroscopic in nature. Desiccants were available either in liquid or solid forms. Solid sorptive materials such as silica gel, Li-Cl and molecular sieves are frequently utilized for different drying applications. The mechanism of a desiccant-powered dehumidification and innovative air-conditioning unit works by adsorbing moisture content of either indoor or ambient humid air. This can be carried out by removing latent heat part of the supplied process air cooling load after exiting the dehumidifier unit. The dehumidification characteristics of the different sorptive desiccants to remove moisture from the process air depend upon moisture content

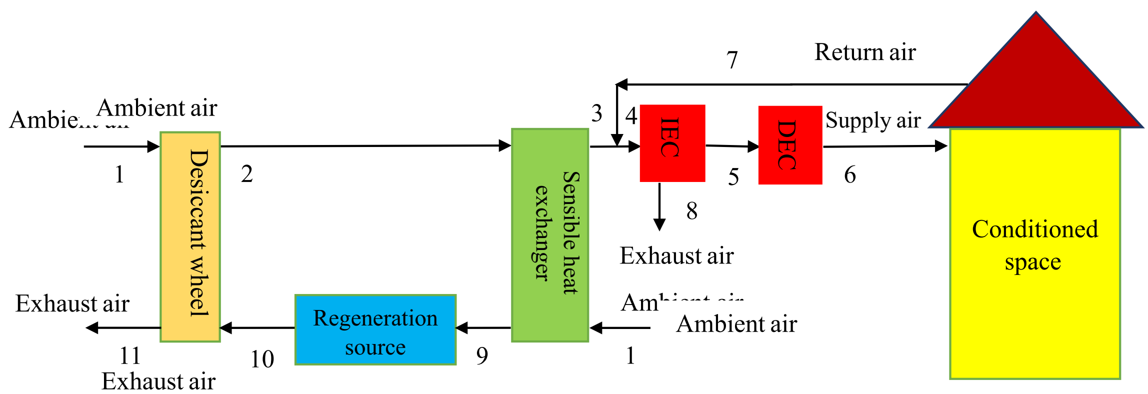
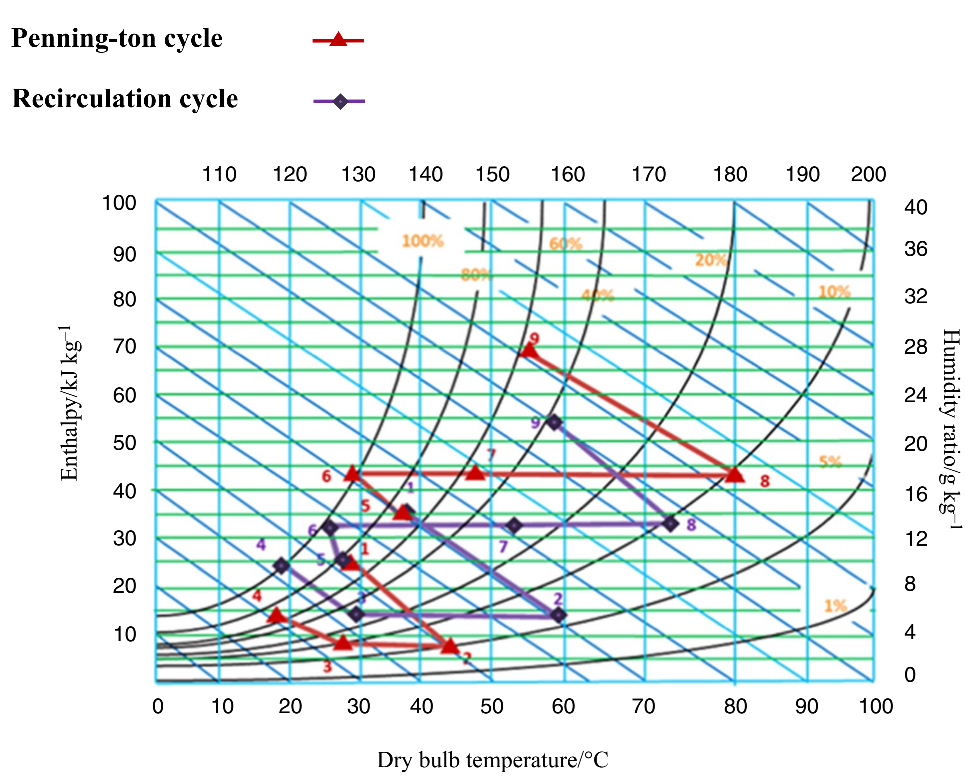


Fig. 6 DINC cycle

Fig. 7 Comparison between Pennington cycle and recirculation cycles



and reactivation temperature of the thermal unit. The water vapour adsorbed in desiccant beds required to be reactivated to work system continually in cycle [80]. The process involves supply of regeneration heat to the saturated desiccant surface to drive off moisture to restore initial condition. Desiccant material used in dehumidifier can be reactivated by variable energy sources include renewable solar heat or industrial waste energy. Slow rotational speed of dehumidifier prevents any leakage among process and regeneration air flow paths.

Different kinds of cooling cycles using solid desiccant are as follows

1. Pennington open cycle (ventilation configuration)
2. Recirculation type closed cycle (recirculation configuration)
3. Dunkle cycle
4. SENS cycle
5. DINC cycle

Pennington cycle

The earliest sorptive cooling cycle works on desiccant dehumidification principle was invented by Pennington which is also called as the ventilation cycle or open desiccant cooling cycle. The rotary wheel at state point 1 dehumidifies the outside air, which raises its temperature because of the reactivation heat supply at regeneration portion among the desiccant wheel matrix, as depicted in Fig. 2. This warm and dry air is sensibly cooled up to the state points 2–3. The same can be cooled further as per room design supply conditions after temperature control by conventional coil at state point 4. In regeneration side of the system, re-circulated room air at state point 5 cools slightly after passing it over sensible cooling coil of conventional air cooler. This can extract the heat from warm air at state point 6 to heat it partially before final reactivation process during state points 7–8. This can save useful final heat addition in the regeneration heater. It can be exhausted to outdoor environment (state point 9) as regeneration process completed at the exit of dehumidifier.

Recirculation cycle

Recirculation cycles, like the one in Fig. 3, are modified Pennington cycles intended to increase cooling capacity by the use of room return air to supply the desiccant wheel process air intake in case of harsh ambient climate [35]. This ameliorates the overall performance of the hybrid cooling system by increasing its cooling efficiency. At the same time, use of hot ambient air as reactivation air can save the heat finally added in reactivation heater.

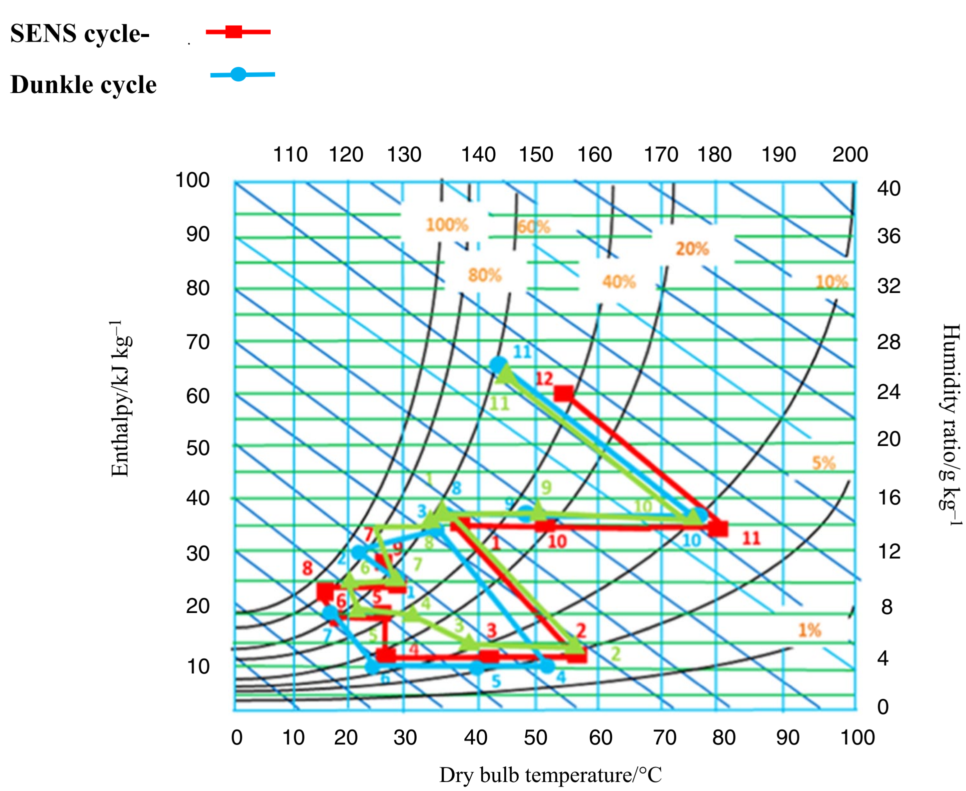


Fig. 8 Comparison among Dunkle, SENS and DINC cycles

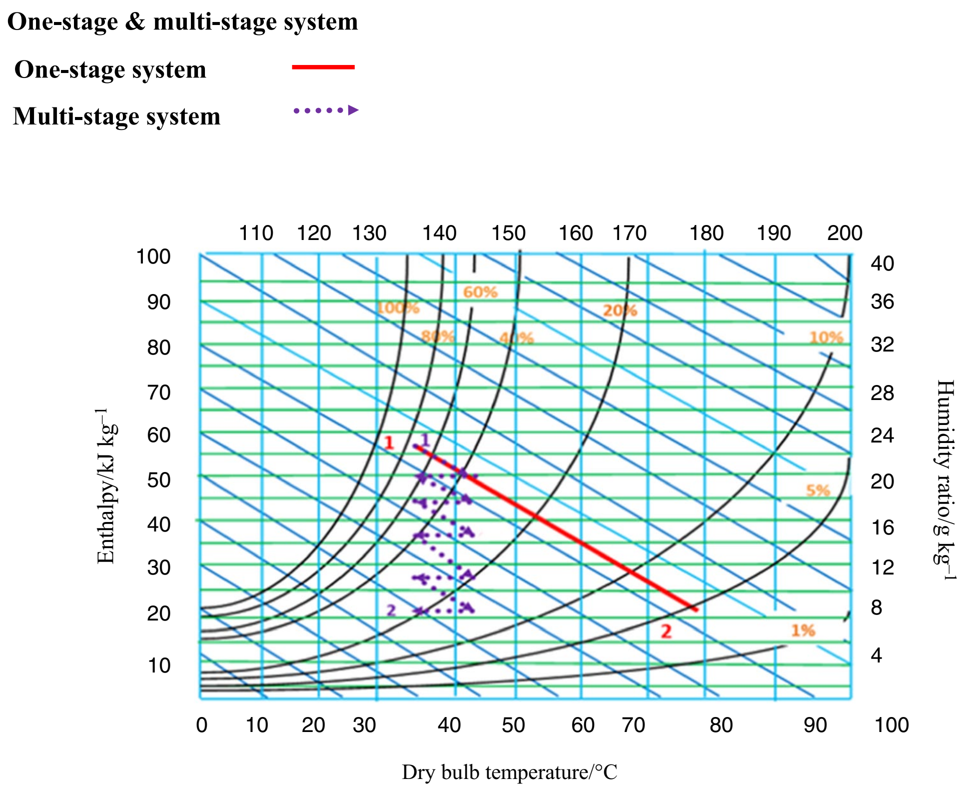


Fig. 9 Psychometric representation of TSDC and OTSDC cycle

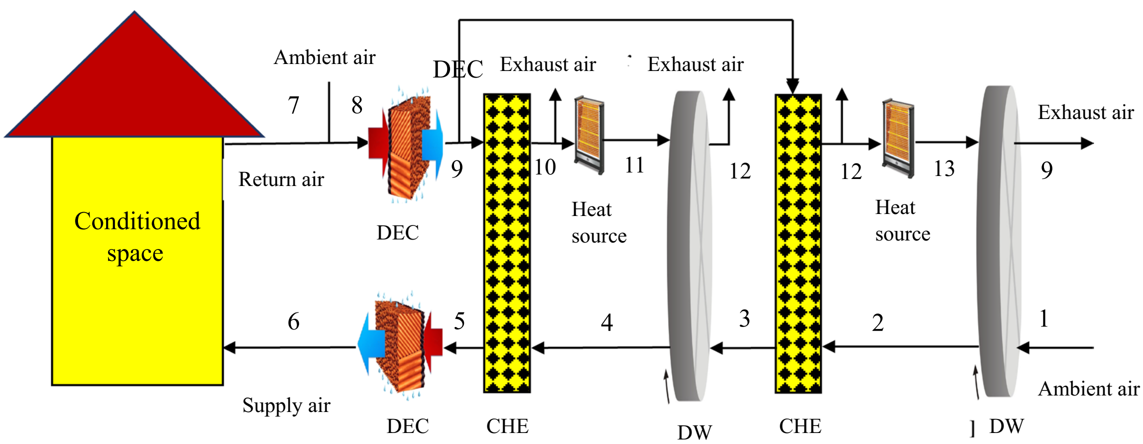


Fig. 10 Dual-stage desiccant-assisted cooling system

Dunkle cycle

As shown in Fig. 4, Dunkle [23] provided two sensible type air-to-air heat recovery units, one is before and another is after the dehumidifier. This can recover the heating and cooling energy between process and reactivation air flows resulted to better overall cooling performance of the cycle. In the system, fresh ventilated air supplied by necessary mixing air flow during return room supply air reactivation. This provision of fresh air can increase additional cooling load is the main drawback of this system.

SENS cycle

In order to address the deficiency of fresh air in earlier cycles, the SENS cycle, an advanced simplified desiccant cycle. The external air in a wheel is initially shown to be dehumidified in Fig. 5, and the action of adsorption heat causes the air to be warm slightly. In this cycle,

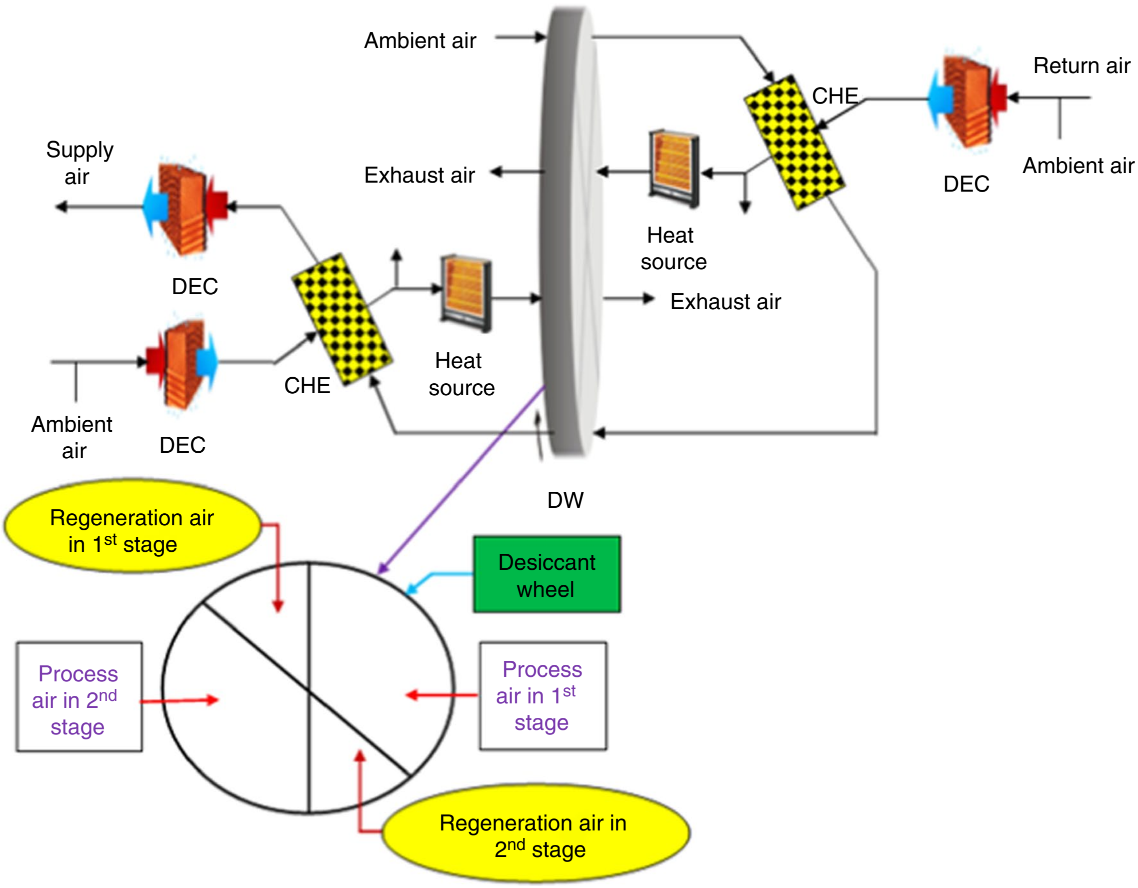
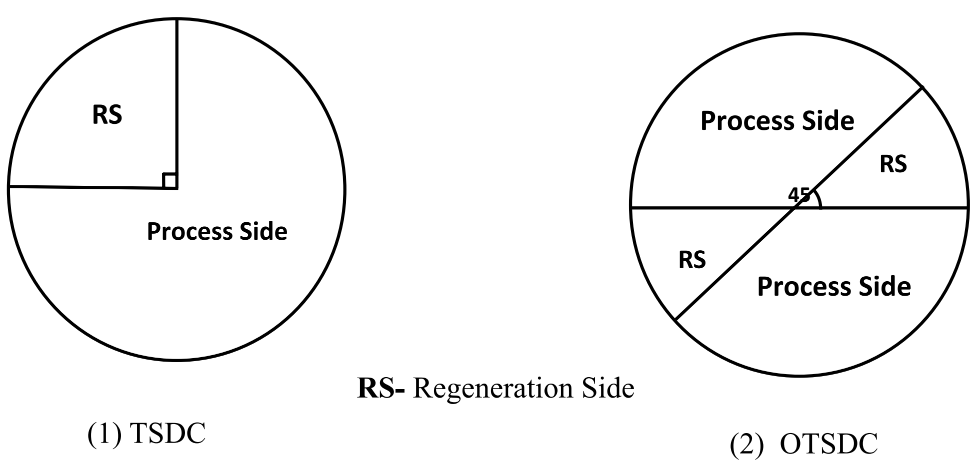


Fig. 11 Single-rotor and dual-stage desiccant dehumidifier

Fig. 12 Schematic diagram of TSDC and OTSDC



two sensible heat exchanges were connected to the dehumidifier and sensible cooler in tandem connection. This can recovered the useful heat of process air section of dehumidifier to regeneration air section of dehumidifier by increasing overall cycle efficiency. The sensible heat exchanger provided on the reactivation side slightly increases the supply temperature of the ambient air side, which is consequently passing to a wheel and exhausted

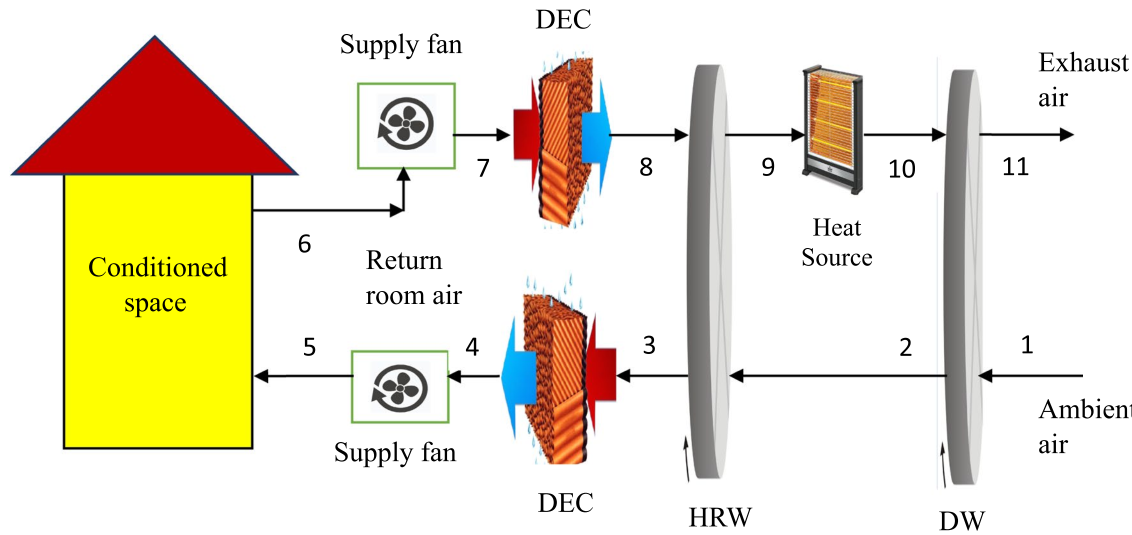


Fig. 13 Solar-powered desiccant-assisted evaporative cooling system (ventilation cycle)

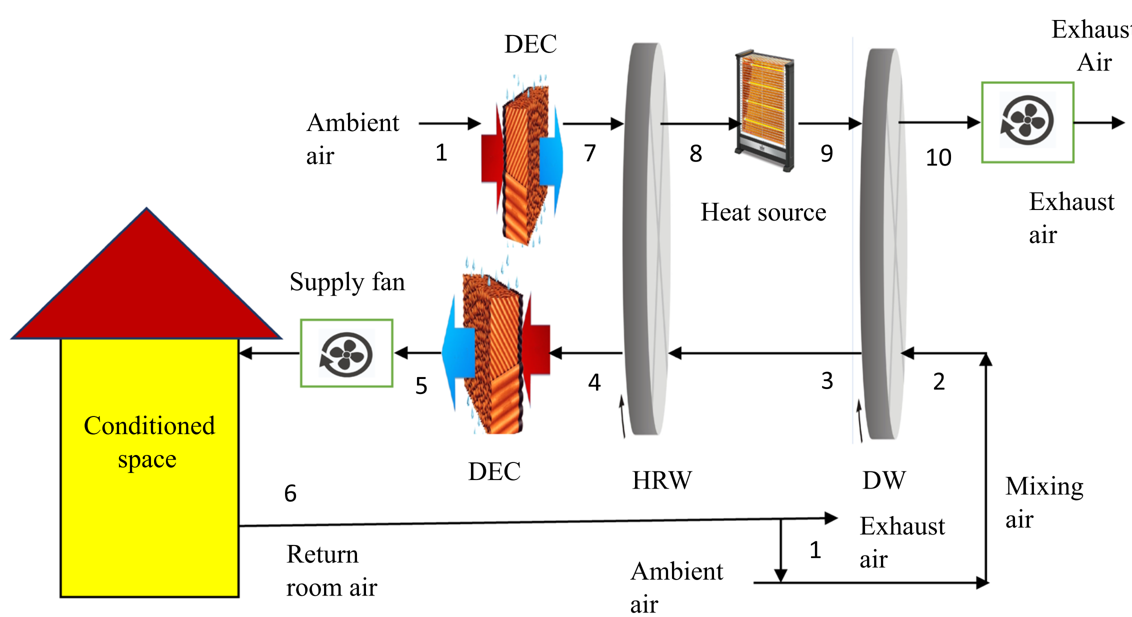


Fig. 14 Solar-powered desiccant-assisted evaporative cooling system (recirculation cycle)

to the outdoor ambient. In climatic circumstances of 26% relative humidity and 26 °C, the SENS cycle's coefficient of performance is greater than 2.0. yielded a about 2.45 coefficient of performance.

DINC cycle

The direct–indirect evaporative type innovative cooling cycle (DINC) assisted by desiccant-based dehumidification cycle is depicted in Fig. 6. To simplify the configuration of the system, sensible heat exchangers were replaced by the use of IEC and DEC in the DINC cycle [36]. This configuration represents a minor modification in the system layout over the SENS cycle. Furthermore, the DINC cycle's performance thermal coefficient has been found to be around 1.6.

Pennington cycle and recirculation cycle

A comparison of the Pennington and recirculation type desiccant dehumidification and innovative cooling cycles is depicted on a psychrometric chart in Fig. 7. Due to a higher humidity ratio at the regeneration air flow section, the psychrometric chart shows that in the event of a recirculation cycle, the regeneration temperature demanded greater heat input to amplify dehumidifier performance. During recirculation air configuration, maximum indoor air can be feed for dehumidification can lower the temperature supply room air temperature to be maintained as per indoor design conditions. Since the Pennington cycle employs just ambient outdoor as process air at the dehumidifier intake, it can be possible to avail maximum fresh ventilated air to the system.

Dunkle cycle, SENS cycle and DINC cycle

In Fig. 8, a brief comparison has been depicted on a psychrometric chart, shows as the ventilation air provision increases can lower overall system performance as well as cooling capacity as compared to conventional cooling cycles. The SENS cycle can give higher overall performance owing to dual heat exchanger in tandem arrangement which will conserve maximum energy from process air to regeneration air streams. But the intricacy of this cycle limits it for better overall cooling performance of the system.

Multi-stage cycles

By the use of the multi-stage cycle, better configuration is achieved to ameliorate adsorption rate achieved through isothermal dehumidification with minimum requirement of regeneration temperature. This can be achieved by provision of intercooler between process and reactivation air flow sections as shown in Fig. 9. A typical two-stage system designed by Ge et al. [37, 38], consists of two desiccant dehumidifiers (TSDC). While Figs. 10 and 11 show innovative two-stage desiccant cooling by splitting single dehumidifier into multiple sectors for the flow of process air stream and reactivation air stream (OTSDC). This can be coupled to coolers and composite matrix material to enhance overall all dehumidification capacities of the cycle [13]. The outcomes verified that both types of innovative dehumidification systems can function at temperatures exceeding 50 °C and achieve a performance coefficient higher than 1.0. As compared to the traditional single-stage cooling, TSDEC cycle can find lower regeneration temperature requirement to give better moisture adsorption rate. The size of OTSDC cycle is small as compared to that of the TSDC for residential applications.

Developments in the configuration of solid desiccant-assisted hybrid cooling systems

Desiccant-assisted dehumidification and innovative cooling systems are mainly classified into the liquid desiccant-based

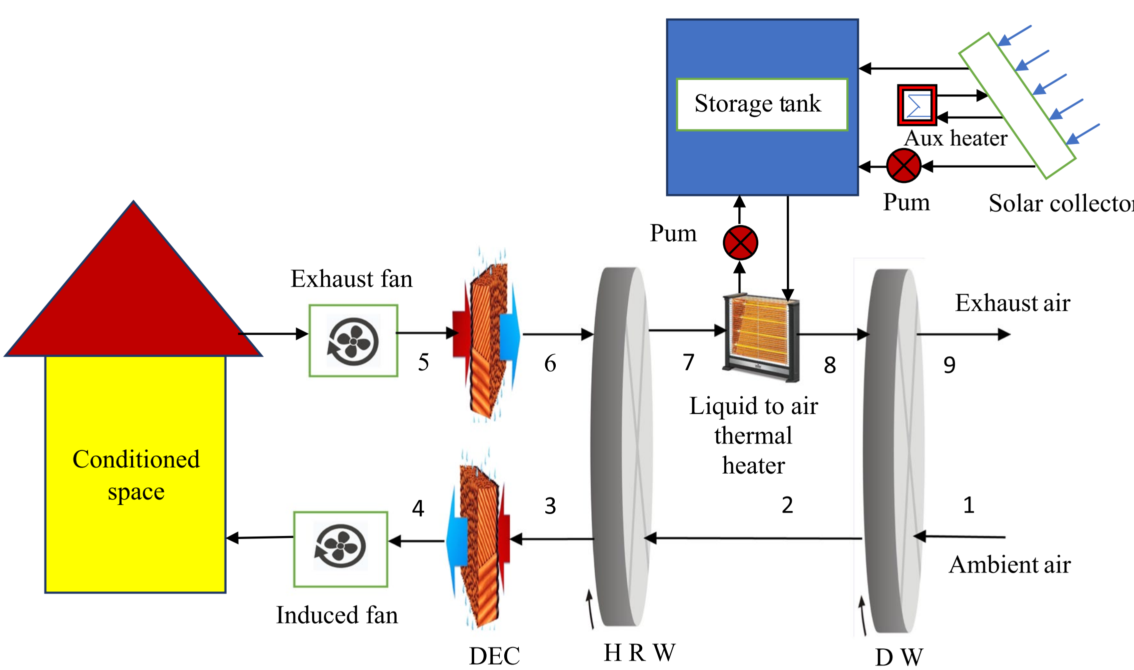


Fig. 15 Ventilation mode for solar-powered desiccant dehumidification-assisted innovative evaporative cooling system

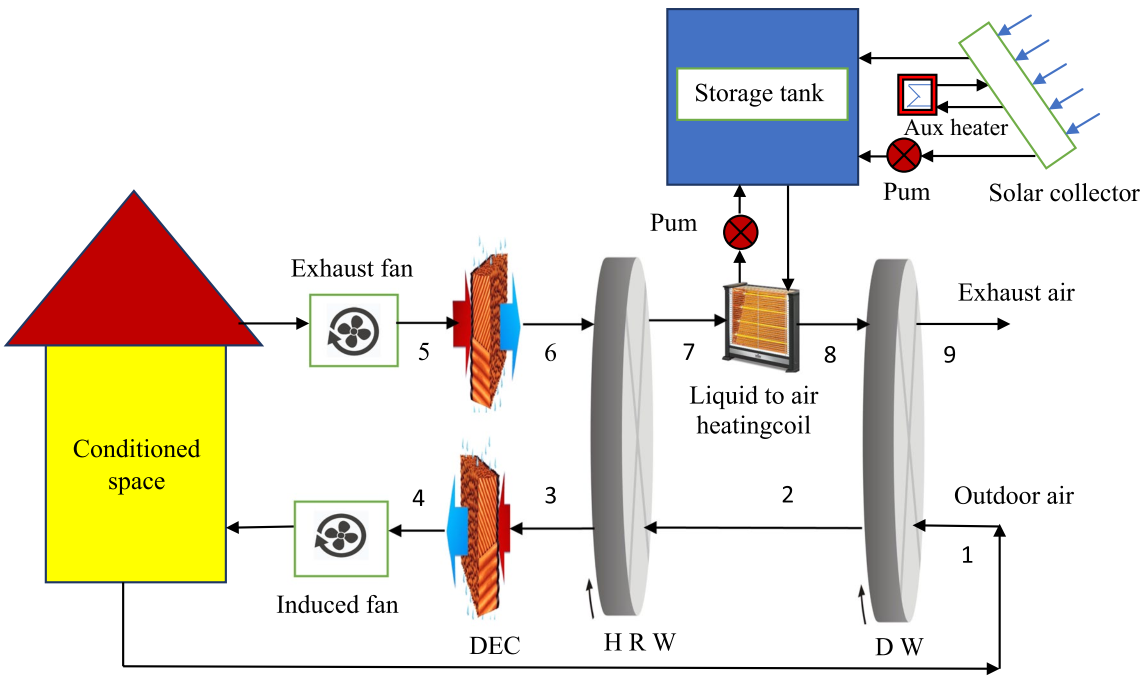


Fig. 16 Recirculation mode for solar-powered desiccant dehumidification-assisted innovative evaporative cooling system

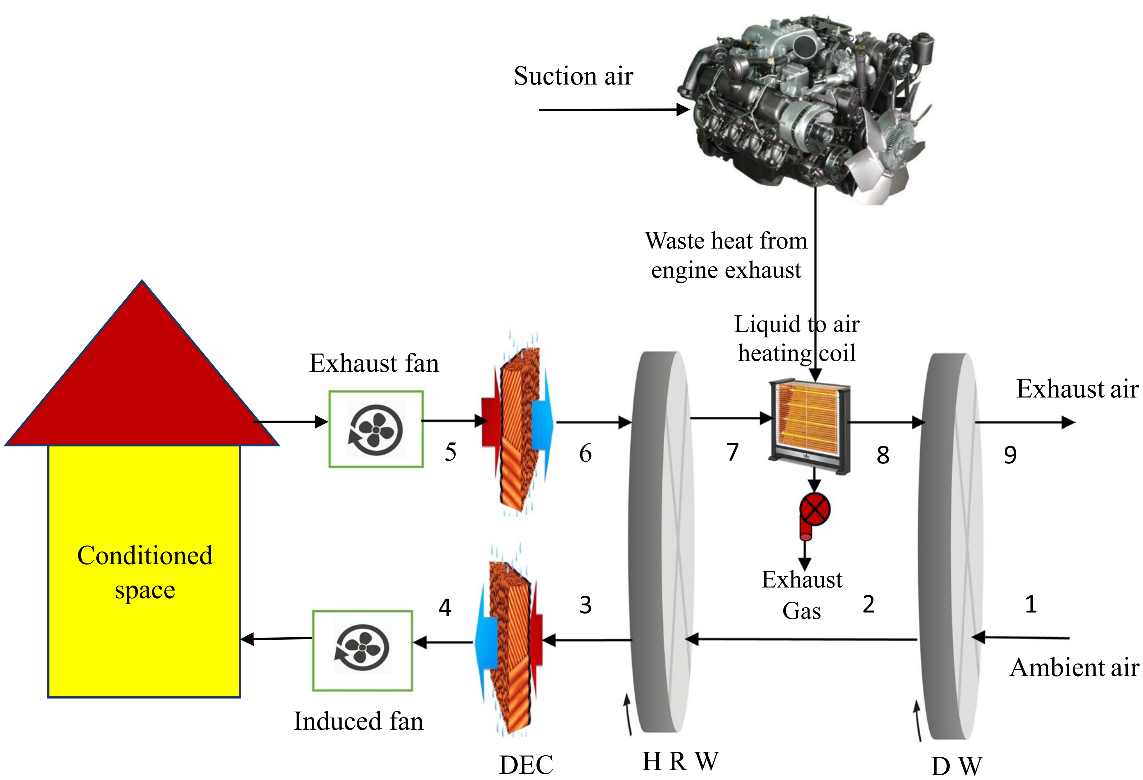


Fig. 17 Supply of engine exhaust as regeneration heat source in hybrid cooling

dehumidification and cooling as well as solid desiccant-based dehumidification and cooling. This is because the sorptive materials can got exist into different states such as liquid or solid. These technologies have been widely utilized as innovative dehumidification and cooling as they are useful in substantial moisture control at the same time can use diversified primary energy sources such as renewable solar energy or industrial cogeneration process waste heat and are free from environmentally harmful CFCs. In particular, rotational desiccant air conditioners are less likely to corrode and operate constantly. In earlier stage, desiccant-based dehumidification and cooling can be subject of numerous empirical studies (Ge et al. [37, 38]; Kabeel [39]), mathematical simulation studies (Zhang et al. [40]; Nia et al. [41]; Ge et al. [42]), second law-based exergy analysis (Kanoǥlu et al. [43, 44]; Shen and Worek [45]) and field applications as per indoor comfort requirements (Casas and Schmitz [46]; Henning et al. [47]; Sand and Fischer [48]). In order to ameliorate the overall system performance, investigators are mainly focus to system configuration and use of diversified viable renewable energy sources or industrial waste heat to lower energy consumption and better economy (Fig. 12).

Evaporative cooling using solid desiccant technology

Desiccant-powered dehumidification and innovative cooling judiciously coupled to air-to-air heating sensible heat exchangers for better performance and cooling capacity. The coolers are either direct or indirect type evaporative one as per existing outdoor climatic conditions. Bourdoukan et al. [49] experimentally concluded that the system being operated in either of the ventilation open cycle or the recirculation closed cycle configuration modes as depicted in Figs. 13 and 14.

Desiccant-assisted evaporative solar cooling system working in ventilation mode

In ventilation mode configuration, solar-powered desiccant cooling system can adsorb moisture from ambient air (state point 1) as shown in Fig. 13. Air-to-air heat recovery wheel used to conserve energy for cooling to supply it for regenerative heating during states 2–3. It can reach to room at state point 5 after passing through direct evaporative cooling. Room return air at state point 6 initially passing through direct evaporative cooler to reduce its temperature partially prior to passing through regenerative heat source (state points 9–10). In last stage exhausted to atmosphere at state point 11 by desorption process for drying the dehumidifier reactivation section.

Desiccant-assisted evaporative solar cooling system operating in recirculation mode

While using recirculation mode of operation as depicted in Fig. 14, the ratio of process air to the regeneration is maintained 75:25 or 50:50 according to variable climatic requirements. About 100% room recirculation air can be used as reactivation air while process air can be mixture of return room air and fresh ventilated air in variable ratio like 80:20 or 60:40 as per occupancy and indoor activity.

Evaporative cooling system with solid desiccant aided by sunlight

The development of solar-aided conventional desiccant-assisted innovative evaporative cooling systems has shown immense potential as a replacement for desiccant dehumidification-powered traditional evaporative cooling systems, which use a significant amount of electricity to run the reactivation heat source. The other configuration is identical to the described schematic arrangement, with the exception that the current system now uses a solar heating system as a regeneration heat source rather than an electric heater. It has a liquid to air heating coil, storage tank, circulating pump, solar collector and backup heater. In renewable solar-powered desiccant dehumidification and innovative cooling systems, heat received from intense solar rays is often transformed into demanded heat for desiccant reactivation energy with the help of different types of solar collectors and PV cells. When intense solar radiations were not available during cloudy weather provision for backup electric heater is made to supply necessary regeneration heat for desiccant reactivation as well as running the fan and motors.

The solar fraction can be denoted as the percentage that represents the ratio of the reactivation heating power provided by the use of solar collectors to the overall driving power of the overall cooling system can be given as follows [50]:

$$\mathrm{SF} = \frac{Q_\mathrm{u}}{Q_\mathrm{t}}$$

where Q_u—thermal energy derived from solar collectors. Q_t—entire cooling system using the solar collectors' energy.

Figure 15 describes schematic layout of the open-cycle ventilation arrangement of the solar-powered desiccant-assisted dehumidification-based innovative cooling system. In which it is seen that the room re-circulated air can be used as reactivation air stream while the ambient air is supplied as a process air.

In recirculation configuration operating mode as depicted in Fig. 16, re-circulated room air is used as process air. Here, reactivation side cycle works in open loop

Table 1 Performance summary of solid desiccant absorption cooling systems with solar assistance

S. no.	Year	Author	Desiccant material	Type of solar collector	COP	Remarks
1	2009	Bourdoukan et al. [51]	–	Evacuated tube	0.45	Solar-powered desiccant-assisted evaporative cooling can be regenerated at comparative intermediate reactivation temperature among 50–70 °C
2	2014	Jribi et al. [52]	Activated carbon	Na	0.1	Overall system cooling performance can be ameliorated by the use of heat and mass recovery
3	2015	Tso et al. [53],	Zeolite	NA	0.16	Overall system performance can be enhanced by 25% greater to that of the conventional system by the use of heat recovery
4	2018	Chen et al. [54]	SAPO-34 zeolite/water	Parabolic trough	0.112–0.13	The dehumidification capacity having nonlinear nature over time period
5	2018	Ahmed et al. [55]	Activated carbon/methanol	Evacuated tube	0.4	While using auxiliary heater solar collector area reduces by one-fourth of the dedicated cooling system
6	2019	Abdelgaied et al. [56]	–	Double path air solar collector	0.48–1.11	Hybrid cooling can be utilized by additional solar collector to maintain reactivation temperature approximately 85 °C
7	2020	Almohammadi and Harby [57]	Silica gel/water	Evacuated tube	0.6	The regeneration temperature above 80 °C can give optimum cooling performance
8	2020	Roumpedakis et al. [58]	Zeolite	Evacuated tube	0.5	EER ratio approximately achieved around 5.8 while maintaining required indoor thermal comfort
9	2020	Robbins and Garimella 2020 [59]	Activated carbon–ammonia	Evacuated tube	0.2–0.4	As compared to solar cycle, thermally activated control can adjust better cooling/heating to meet optimum cooling performance
10	2020	Alahmer et al. [60]	Silica gel/water	Parabolic trough	0.5	System performance achieved in range of 0.4–0.5 for commercial building during daytime when ample solar energy available for reactivation
11	2021	Sha and Baiju [61]	Activated carbon	Parabolic trough	0.68	While adsorption temperature rises chilled water temperature reduces to lower the overall cooling performance of the cycle
12	2021	Liu et al. [62]	Silica gel/water	Tracked parabolic trough	0.258	Application of silica gel is found greater cooling performance of the cycle as compared to utilization of zeolite

Table 2 Performance summary of solid desiccant absorption cooling systems with solar assistance

S. no.	Year	Investigator	Type of solar collector used	Approx. area of solar collector/m^{-2}	COP	Tempt range
1	2015	Sun et al. [63]	Evacuated tube	1020	0.75	84–90
2	2017	Bellos and Tzivanidis [64]	Evacuated tube	10–60	0.7	10–60
3	2020	Aguilar-Jiménez et al. [65]	Evacuated tube	110.25	0.7	75–95
4	2020	Arabkoohsar and Sadi [66]	Parabolic trough	39	0.715	397–541
5	2020	Altun and Kilic [67]	Evacuated tube	30	0.76	90–105
6	2020	Arabkoohsar and Sadi [68]	Parabolic trough	39	0.75	86–108
7	2021	Narayanan et al. [69]	Evacuated tube	4.15	0.65	70–95
8	2021	Nikbakhti and Iranmanesh [70]	Flat plate solar	34	0.32–0.37	60
9	2021	AmiriRad and Davoodi [71]	Evacuated tube	100	0.8078	50–150

as described by Dezfouli et al. [50]. Reactivation energy supply for desiccant reactivation can be aided by renewable solar heat by the provision of solar collector and liquid to air heating thermal heater. Auxiliary heater is also provided to continue heat supply in case of cloudy weather when sun radiations were mild.

Waste heat recovery system with desiccant-powered innovative evaporative cooling

In desiccant-powered innovative evaporative cooling system, the rotational dehumidifier may be replenished by heat recovery using either the micro-CHP unit or the engine exhaust of DG set (Fig. 17). This improved fuel efficiency with increased engine thermal efficiency at the same time cooling performance of the desiccant-powered dehumidification and innovative evaporative cooling HVAC system.

The table below provides a summary of the solar-assisted desiccant dehumidification-based innovative evaporative desiccant cooling system's dehumidification as well as overall cooling performance, including the types of solar collectors, their areas and performance index. It is founded on earlier study projects completed by several scholars in accordance with distinct climatic zones found in diverse regions of the world (Tables 1–4).

Mathematical model

In order to carry out design of desiccant wheel and experimental result analysis, mathematical model [88, 89, 102–112] has been described as given below.

Humidity ratio

Humidity ratio (W) for the humid air can be given as the ratio of the mass of water vapour present in humid air (mw) to mass of dry air (ma) as per following [113–115] relation:

$$W = \frac{m_{\mathrm{w}}}{m_{\mathrm{a}}} = \frac{(Pw \times V/R \times T)_{\mathrm{w}}}{(Pa \times V/R \times T)_{\mathrm{a}}} \tag{1}$$

Relative humidity

Relative humidity (ϕ_{r}) of moist air mixture is the ratio of the actual water vapour pressure to the saturation water vapour pressure exerted at the same [116, 117] temperature

$$\phi r = \frac{P_{\mathrm{w}}}{P_{\mathrm{ws}}} \tag{2}$$

Enthalpy

Enthalpy is the total amount of useful heat energy stored within the air–water vapour mixture [120–121]. The enthalpy of moist air can be observed as for following temperature range $-50\ °C \leq tdb \leq 110\ °C$:

$$h = 1.006 \times t_{\mathrm{db}} + W \times \left(2501 + 1.805 \times t_{\mathrm{db}}\right) \tag{3}$$

Table 3 Summary of parameter studied by the previous experimental work

Sl. no.	Type of sorptive material used	Speed/rph	Regeneration temp/°C	Desiccant wheel dimension (dia./thickness) (m)	Vol. flow rate/m^{-3} h		Process air inlet conditions		COP	References
					Process air	Reg. air	Temp/°C	Humidity ratio/g kg^{-1}		
1	Silica gel Li-Cl	–	85	2.8/0.1	–	–	34	22	3.2	La et al. [72]
2	Silica gel	13	80	0.6/0.2	900	800	32.8	23.4	0.8	Fong et al. [73]
3	Silica gel	8	50–90	0.44/0.1	2600	1000	34	22	1.0	La et al. [74]
4	Silica gel	–	68.95	0.96/0.2	4000	4000	31.9	16.9	–	Hurdogan et al. [75]
5	Silica gel	6	50–80	0.63/0.2	600–1500	600–1500	32–36	7–10.2	0.4–0.8	Panaras et al. [76]
6	Metal silicate	24.5	–	0.45/0.2	250–750	250–750	32	21	1.0–2.5	Subramanyam et al. [77]
7	Li-Cl	7	60–120	0.32/0.2	400–1000	300	30	19	2.5–3	Yong et al. [78]
8	Li-Cl	7	100	0.23/0.2	–	–	30.5	14.9	4.8	Jia et al. [79]
9	Natural zeolite	-	60.8	0.5/0.25	400	400	31.5	9.5	0.34	Kanoglu et al. [80]
10	Silica gel	7–10	65	-	800	0–800	25.6–34.3	8.63–11.5	0.3–0.9	Angrisani et al. [81]

Density

The density (d) of a moist air and water vapour mixture is the ratio of the total mass (air and water) to the total volume can be given as following:

$$d = \frac{m_a + m_w}{V} \quad (4)$$

Specific cooling capacity

The specific cooling capacity of sensible cooler in terms of the total supplied process air can be expressed as following relation:

$$\Delta H = h_1 - h_3 \quad (5)$$

Total moisture removal capacity

Total moisture removal capacity of desiccant rotary dehumidifier given in terms of total supplied process air can be denoted by following formulae:

$$M_{PS} = m_1 \times (w_1 - w_2) \quad (6)$$

The rate of moisture desorbed by the regeneration air during desiccant reactivation can be expressed by the following relation:

$$M_{RS} = m_1 \times (w_6 - w_5) \quad (7)$$

The cooling effect

The cooling effect Q_c of desiccant-assisted innovative cooling system can be expressed by following relation:

$$Q_c = m_2 \times \Delta H \quad (8)$$

Coefficient of performance

Coefficient of performance (COP) is denoted as ratio of total cooling capacity of the sensible cooler of the system and air heater enthalpy drop, and it can be obtained as follows:

$$COP = \frac{h_3 - h_1}{h_5 - h_4} \quad (9)$$

Desiccant wheel effectiveness

The desiccant wheel effectiveness (ψ_{ABS}) during adsorption process can be denoted by the following formulae:

Table 4 An overview of current research on various hybrid solid desiccant air conditioner designs

Year	References	Method	Regeneration source	Description
1975	Rush et al. [82]	Experimental	Solar energy, natural gas	Solar-powered hybrid cooling installation
1987	Joudi et al. [83]	Experimental	Renewable solar heat	Solar-powered desiccant-integrated innovative evaporative cooling
1994	San et al. [84]	Experimental	Solar energy	Silica gel packed-bed desiccant dehumidification-based cooling system—modelling and testing
1998	Singh et al. [85]	Experimental	Solar energy	Silica gel-assisted regeneration in multi-shelf regenerator unit
1999	Techajunta et al. [86]	Experimental	Solar energy	Experimental findings for tropical climate for solar-powered desiccant-assisted hybrid cooling
2005	Ando and Kodama [87]	Experimental	Gas engine heat pump or micro-CHP	Desiccant-powered innovative evaporative cooling system with double-stage dehumidification having system performance in range 0.4–0.5
2005	Azar et al. [88]	Experimental	IC engine waste heat	Desiccant-assisted hybrid cooling with CHP coupling having electrical COP evaluated approximately near 5
2006	Qin and Schmitz [89]	Experimental	Waste heat from engine exhaust	Desiccant-integrated innovative cooling reactivation achieved by the use of an engine exhaust having approximately one-third energy saving as compared to conventional system
2006	Kohlenbach et al. [90]	TRNSYS simulation	Micro-turbine waste heat	Desiccant-assisted evaporative cooling regenerated by micro-turbine exhaust heat and system performance achieved near 3
2006	Zhuo et al. [91]	Experimental	Renewable solar heat	Experimental evaluation of desiccant-based hybrid cooling reactivated by the use of renewable solar heat
2007	Kabeel [92]	Experimental	Solar asisted	Desiccant-based honeycomb rotary dehumidifier-powered air cooling reactivated by renewable solar energy
2008	Ge et al. [93]	Experimental	Solar energy	Performance evaluation of one-rotor two-stage desiccant wheel reactivated by renewable solar energy
2010	Yilmaz et al. [94]	Experimental	Electric heater	Experimental performance of two-stage innovative desiccant-based hybrid cooling system
2010	Ge et al. [95]	Experimental	Solar energy	Performance comparison between solar-assisted desiccant-based innovative cooling system and conventional VCR base air-conditioning system
2011	Angrisani et al. [96]	Experimental	Thermal waste of the cogeneration	Hybrid desiccant cooling integrated to micro-cogenerator having 30–35% lower carbon dioxide emission as well as 18–20% lower electricity consumption
2011	Ge et al. [97]	Simulation and experimental	Condenser dissipated heat	Air source heat pump (ASHP) unit can achieve greater savings in cooling as well as heating operating configurations
2014	El-Agouz and Kabeel [98]	Experimental and simulation	Geothermal energy	Use of geothermal heat can reduce primary energy consumption for the desiccant-integrated hybrid cooling

Table 4 (continued)

Year	References	Method	Regeneration source	Description
2014	Ying et al. [99]	Experimental	Condenser of heat pump	Heat pump coupled desiccant cooling having overall system cooling performance in range 05.-2.5
2015	Angrisani et al. [100]	Experimental	Industrial waste heat	Comparison among desiccant-integrated innovative cooling and vapour compression-based traditional cooling system
2016	Angrisani et al. [101]	TRNSYS simulation	Geothermal source	Use of geothermal heat can reduce primary energy consumption for the desiccant-integrated hybrid cooling

$$\psi_{ABS} = \frac{W_1 - W_2}{W_1 - W_{2\,ideal}} \tag{10}$$

where w_{2ideal} is the ideal sp. humidity of dry air exited from the rotary dehumidifier. If the air is absolutely dehumidified at this point, the effectiveness of dehumidifier is assumed to be zero.

The ratio of the variation in air humidity level throughout the reactivation process to the air's input humidity is known as the wheel effectiveness (ψ_{REG}).

$$\psi_{REG} = \frac{W_6 - W_5}{W_5} \tag{11}$$

Conclusions

The review can enumerate different reactivation techniques for desiccant-assisted innovative cooling systems through the present study. For many years, desiccant dehumidification-assisted innovative cooling system has been an established and effective method to control indoor comfort as per climatic applicability in different geographic locations. Nonetheless, desiccant dehumidification-assisted innovative cooling technology will undoubtedly have good alternative as compared to the traditionally used vapour compression-based air-conditioning systems if the cost of these systems is reduced, and they function better for variable climate. In the near future, desiccant dehumidification devices should be able to address the issues that the HVAC sector is now facing for intensive humidity control in different industrial and residential applications. In order to ameliorate overall cooling performance of the system and lower utility for high-grade electricity demands in power plants which usually uses fossil fuels, national standards development has been recommitted due to factors such as increased demand for the higher ventilation flow rates, better IAQ (indoor air quality), advanced humidity control levels and the get rid of environmentally harmful CFCs. These factors at the same time focus on augmenting desiccant-based innovative cooling techniques can be a key to the sustainable and green cooling solutions in the field of HVAC. Further research in the field of desiccant which reactivated nearly to the ambient conditions makes it feasible and appropriate cooling technology of the future HVAC.

References

1. Yadav AV. Experimental and numerical investigation of solar powered solid desiccant dehumidifier. PhD thesis, National Institute of Technology, Kurukshetra. 2012.
2. Reza M, Wahed A, Constanze BK. Two-stage air-dehumidification system for the tropics-experimental and theoretical analysis of a lab system. Energy. 2014;8:982–90. https://doi.org/10.1016/j.egypro.2014.02.112.
3. Ruivo CR, Angrisani G. The effectiveness method to predict the behaviour of a desiccant wheel: an attempt of experimental validation. App Thermal Eng. 2014;71(2):643–51. https://doi.org/10.1016/j.applthermaleng.2013.10.028.
4. Henning HM, Pagano T, Mola S, Wiemken E. Micro tri-generation system for indoor air conditioning in the Mediterranean climate. App Thermal Eng. 2007;27(13):2188–94. https://doi.org/10.1016/j.applthermaleng.2005.07.031.
5. Capozzoli A, Mazzei P, Minichiello F, Palma D. Hybrid HVAC systems with chemical dehumidification for supermarket applications. App Thermal Eng. 2006;26(8–9):795–805. https://doi.org/10.1016/j.applthermaleng.2005.10.014.
6. Xiao F, Ge G, Niu X. Control performance of a dedicated outdoor air system adopting liquid desiccant dehumidification. Appl Energy. 2011;88(1):143–9. https://doi.org/10.1016/j.apenergy.2010.06.019.
7. Ge G, Xiao F, Xu X. Model-based optimal control of a dedicated outdoor air-chilled ceiling system using liquid desiccant and membrane-based total heat recovery. Appl Energy. 2011;88(11):4180–90. https://doi.org/10.1016/j.apenergy.2011.04.045.
8. Angrisani G, Capozzoli A, Minichiello F, Roselli C, Sasso M. Desiccant wheel regenerated by thermal energy from a microcogenerator: experimental assessment of the performances. Appl Energy. 2011;88(4):1354–65. https://doi.org/10.1016/j.apenergy.2010.09.025.
9. Calise F, d'Accadia MD, Roselli C, Sasso M, Tariello F. Desiccant-based AHU interacting with a CPVT collector: simulation of energy and environmental performance. Sol Energy.

2014;103:574–94. https://doi.org/10.1016/j.solener.2013.11.001.
10. Wang X, Cai W, Lu J, Sun Y, Ding X. A hybrid dehumidifier model for real-time performance monitoring, control and optimization in liquid desiccant dehumidification system. Appl Energy. 2013;111:449–55. https://doi.org/10.1016/j.apenergy.2013.05.026.
11. Qi R, Lu L, Yang H, Qin F. Investigation on wetted area and film thickness for falling film liquid desiccant regeneration system. Appl Energy. 2013;112:93–101. https://doi.org/10.1016/j.apenergy.2013.05.083.
12. Angrisani G, Roselli C, Sasso M, Tariello F. Dynamic performance assessment of a micro-trigeneration system with a desiccant-based air handling unit in Southern Italy climatic conditions. Energy Convers Manage. 2014;80:188–201. https://doi.org/10.1016/j.enconman.2014.01.028.
13. Ge TS, Dai YJ, Li Y, Wang RZ. Simulation investigation on solar powered desiccant coated heat exchanger cooling system. Appl Energy. 2012;93:532–40. https://doi.org/10.1016/j.apenergy.2011.11.089.
14. Maclaine-cross IL. High-performance adiabatic desiccant open-cooling cycles. J Sol Energy Eng. 1985;107(1):102–4. https://doi.org/10.1115/1.3267637.
15. Henning HM. Solar assisted air conditioning of buildings-an overview. Appl Therm Eng. 2007;27(10):1734–49. https://doi.org/10.1016/j.applthermaleng.2006.07.021.
16. Collier RK, Cohen BM. An analytical examination of methods for improving the performance of desiccant cooling systems. J Sol Energy Eng. 1991;113(3):151–63. https://doi.org/10.1115/1.2930487.
17. Worek WM, Zheng W, Belding WA, Novosel D, Holeman WD. Simulation of advanced gas-fired desiccant systems. ASHRAE Trans. 1991;97(2):609–14.
18. Dhar PL, Singh SK. Studies on solid desiccant based hybrid air-conditioning systems. Appl Therm Eng. 2001;21(2):119–34. https://doi.org/10.1016/S1359-4311(00)00035-1.
19. Fong KF, Lee CK, Chow TT, Fong AM. Investigation on solar hybrid desiccant cooling system for commercial premises with high latent cooling load in subtropical Hong Kong. Appl Therm Eng. 2011;31(16):3393–401. https://doi.org/10.1016/j.applthermaleng.2011.06.024.
20. Khalid A, Mahmood M, Asif M, Muneer T. Solar assisted, pre-cooled hybrid desiccant cooling system for Pakistan. Renew Energy. 2009;34(1):151–7. https://doi.org/10.1016/j.renene.2008.02.031.
21. Fatouh M, Ibrahim TA, Mostafa A. Experimental investigation on a solid desiccant system integrated with a R407C compression air conditioner. Energy Convers Manage. 2009;50(10):2670–9. https://doi.org/10.1016/j.enconman.2009.06.020.
22. Pennington NA. Humidity changer for air conditioning. USA patent no. 2,700,537;1955.
23. Dunkle RV. A method of solar air conditioning. Mech Chem Eng Trans Inst Eng. 1965;73:73–8.
24. Munters CG. In organic, fibrous, gas-conditioning packing for heat and moisture transfer.U.S.patent 3,377,225;1968.
25. Shelpuk BC, Hooker DW. Development program in solar desiccant cooling for residential buildings. Int J Refrig. 1979;2:173–9.
26. Jurinak JJ. Open cycle solid desiccant cooling-component models and system simulation. Ph.D. thesis, Madison: University of Wisconsin,1982.
27. Pesaran AA, Mills AF. Modeling of solid-side mass transfer in desiccant particle beds. Sol Eng. 1984;177–85.
28. Sheridan S. Evaluation and optimization of solar desiccant wheel performance. Renew Energy. 1985;30:305–25.
29. Farooq KD, Ruthven DM. Numerical simulation of a desiccant bed for solar air heater conditioning applications. Solar Energy Eng. 1991;113:80–92.
30. Jain S, Dhar PL, Kaushik SC. Evaluation of solid-desiccant-based evaporative cooling cycles for typical hot and humid climates. Int J Ref. 1995;18(5):287–96. https://doi.org/10.1016/0140-7007(95)00016-5.
31. Belding WA, Delmas MPF. Novel desiccant cooling system using indirect evaporative cooler. ASHRAE Trans. 1997;103:841–7.
32. Kabeel AE. Solar powered air conditioning system using rotary honeycomb desiccant wheel. Renew Energy. 2007;32(11):1842–57. https://doi.org/10.1016/j.renene.2006.08.009.
33. Panaras G, Mathioulakis E, Belessiotis V. Achievable working range for solid all-desiccant air-conditioning systems under specific space comfort requirements. Energy Build. 2007;39(9):1055–60. https://doi.org/10.1016/j.enbuild.2006.10.015.
34. Daou K, Wang RZ, Xia ZZ. Desiccant cooling air conditioning: a review. Renew Sustain Energy Rev. 2006;10(2):55–77. https://doi.org/10.1016/j.rser.2004.09.010.
35. Dadi MJ, Jani DB. Experimental investigation of solid desiccant wheel in hot and humid weather of India. Int J Ambient Energy. 2022;43(1):5983–91. https://doi.org/10.1080/01430750.2021.1999326.
36. La D, Dai YJ, Li Y, Wang RZ, Ge TS. Technical development of rotary desiccant dehumidification and air conditioning: a review. Renew Sustain Energy Rev. 2010;14(1):130–47. https://doi.org/10.1016/j.rser.2009.07.016.
37. Ge TS, Dai YJ, Wang RZ, Li Y. Experimental investigation on a one-rotor two-stage rotary desiccant cooling system. Energy. 2008;33(12):1807–15. https://doi.org/10.1016/j.energy.2008.08.006.
38. Ge TS, Li Y, Wang RZ, Dai YJ. Experimental study on a two-stage rotary desiccant cooling system. Int J Refrig. 2009;32(3):498–508. https://doi.org/10.1016/j.ijrefrig.2008.07.001.
39. Dai YJ, Wang RZ, Zhang HF. Use of liquid desiccant cooling to improve the performance of vapour compression air conditioning. Appl Therm Eng. 2001;21:1185–202. https://doi.org/10.1016/S1359-4311(01)00002-3.
40. Luo Y, Wang M, Yang H, Lu L, Peng J. Experimental study of internally cooled liquid desiccant dehumidification: application in Hong Kong and intensive analysis of influencing factors. Build Environ. 2015;93:210–20. https://doi.org/10.1016/j.buildenv.2015.05.022.
41. Kanoğlu M, Çarpınlıoğlu MÖ, Yıldırım M. Energy and exergy analyses of an experimental open-cycle desiccant cooling system. Appl Therm Eng. 2004;24(5–6):919–32. https://doi.org/10.1016/j.applthermaleng.2003.10.003.
42. Kanoğlu M, Bolattürk A, Altuntop N. Effect of ambient conditions on the first and second law performance of an open desiccant cooling process. Renew Energy. 2007;32(6):931–46. https://doi.org/10.1016/j.renene.2006.04.001.
43. Shen CM, Worek WM. The second-law analysis of a recirculation cycle desiccant cooling system: cosorption of water vapor and carbon dioxide. Atmos Environ. 1996;30(9):1429–35. https://doi.org/10.1016/1352-2310(95)00437-8.
44. Casas W, Schmitz G. Experiences with a gas driven, desiccant assisted air conditioning system with geothermal energy for an office building. Energy Build. 2005;37(5):493–501. https://doi.org/10.1016/j.enbuild.2004.09.011.
45. Henning HM, Erpenbeck T, Hindenburg C, Santamaria IS. The potential of solar energy use in desiccant cooling cycles. Int J Refrig. 2001;24(3):220–9. https://doi.org/10.1016/S0140-7007(00)00024-4.

46. Sand JR, Fischer JC. Active desiccant integration with packaged rooftop HVAC equipment. Appl Therm Eng. 2005;25(17–18):3138–48. https://doi.org/10.1016/j.applthermaleng.2005.04.007.
47. Bourdoukan P, Wurtz E, Joubert P. Comparison between the conventional and recirculation modes in desiccant cooling cycles and deriving critical efficiencies of components. Energy. 2010;35:1057–67. https://doi.org/10.1016/j.energy.2009.06.021.
48. Dezfouli MM, Mat S, Pirasteh G, Sahari KS, Sopian K, Ruslan MH. Simulation analysis of the four configurations of solar desiccant cooling system using evaporative cooling in tropical weather in Malaysia. Int J Photo Energy. 2014. https://doi.org/10.1155/2014/843617.
49. Bourdoukan P, Wurtz E, Joubert P. Experimental investigation of a solar desiccant cooling installation. Sol Energy. 2009;83:2059–73. https://doi.org/10.1016/j.solener.2009.08.005.
50. Jribi S, Saha BB, Koyama S, Bentaher H. Modeling and simulation of an activated carbon–CO2 four bed based adsorption cooling system. Energy Convers Manag. 2014;78:985–91. https://doi.org/10.1016/j.enconman.2013.06.061.
51. Tso CY, Chan KC, Chao CYH, Wu CL. Experimental performance analysis on an adsorption cooling system using zeolite 13X/CaCl2 adsorbent with various operation sequences. Int J Heat Mass Transf. 2015;85:343–55. https://doi.org/10.1016/j.ijheatmasstransfer.2015.02.005.
52. Chen QF, Du SW, Yuan ZX, Sun TB, Li YX. Experimental study on performance change with time of solar adsorption refrigeration system. Appl Therm Eng. 2018;138:386–93. https://doi.org/10.1016/j.applthermaleng.2018.04.061.
53. Ahmed MH, El-Ghetany H, Boushaba H. Comparison of the thermal performance of solar adsorption cooling system between Egypt and Morocco. Appl Sol Energy. 2018;54:361–8. https://doi.org/10.3103/S0003701X1805002X.
54. Abdelgaied M, Kabeel AE, Zakaria Y. Performance improvement of desiccant air conditioner coupled with humidification-dehumidification desalination unit using solar reheating of regeneration air. Energy Convers Manag. 2019;198:111–808. https://doi.org/10.1109/IREC.2018.8362568.
55. Almohammadi KM, Harby K. Operational conditions optimization of a proposed solar-powered adsorption cooling system: Experimental, modeling and optimization algorithm techniques. Energy. 2020;206:118007. https://doi.org/10.1016/j.energy.2020.118007.
56. Roumpedakis TC, Vasta S, Sapienza A, Kallis G, Karellas S, Wittstadt U, Tanne M, Harborth N, Sonnenfeld U. Performance results of a solar adsorption cooling and heating unit. Energies. 2020;13:1630. https://doi.org/10.3390/en13071630.
57. Robbins T, Garimella S. An autonomous solar driven adsorption cooling system. Sol Energy. 2020;211:1318–24. https://doi.org/10.1016/j.solener.2020.10.068.
58. Alahmer A, Wang X, Alam KCA. Dynamic and economic investigation of a solar thermal-driven two-bed adsorption chiller under perth climatic conditions. Energies. 2020;13:1005. https://doi.org/10.3390/en13041005.
59. Sha AA, Baiju V. Thermodynamic analysis and performance evaluation of activated carbon-ethanol two-bed solar adsorption cooling system. Int J Refrig. 2021;123:81–90. https://doi.org/10.1016/j.ijrefrig.2020.12.006.
60. Liu YM, Yuan ZX, Wen X, Du CX. Evaluation on performance of solar adsorption cooling of silica gel and SAPO-34 zeolite. Appl Therm Eng. 2021;182:116019. https://doi.org/10.1016/j.applthermaleng.2020.116019.
61. Sun H, Xu Z, Wang H, Wang R. A solar/gas fired absorption system for cooling and heating in a commercial building. Energy Procedia. 2015;70:518–28. https://doi.org/10.1016/j.egypro.2015.02.156.
62. Bellos E, Tzivanidis C. Energetic and financial analysis of solar cooling systems with single effect absorption chiller in various climates. Appl Therm Eng. 2017;126:809–21. https://doi.org/10.1016/j.applthermaleng.2017.08.005.
63. Aguilar-Jiménez JA, Velázquez-Limón N, López-Zavala R, González-Uribe LA, Islas S, González E, Ramírez L, Beltrán R. Optimum operational strategies for a solar absorption cooling system in an isolated school of Mexico. Int J Refrig. 2020;112:1–13. https://doi.org/10.1016/j.ijrefrig.2019.12.010.
64. Arabkoohsar A, Sadi M. A solar PTC powered absorption chiller design for co-supply of district heating and cooling systems in Denmark. Energy. 2020;193:116789. https://doi.org/10.1016/j.energy.2019.116789.
65. Altun AF, Kilic M. Economic feasibility analysis with the parametric dynamic simulation of a single effect solar absorption cooling system for various climatic regions in Turkey. Renew Energy. 2020;152:75–93. https://doi.org/10.1016/j.renene.2020.01.055.
66. Arabkoohsar A, Sadi M. Technical comparison of different solar-powered absorption chiller designs for co-supply of heat and cold networks. Energy Convers Manag. 2020;206:112343. https://doi.org/10.1016/j.enconman.2019.112343.
67. Narayanan R, Harilal GK, Golder S. Feasibility study on the solar absorption cooling system for a residential complex in the Australian subtropical region. Case Stud Therm Eng. 2021;27:101202. https://doi.org/10.1016/j.csite.2021.101202.
68. Nikbakhti R, Iranmanesh A. Potential application of a novel integrated adsorption–absorption refrigeration system powered with solar energy in Australia. Appl Therm Eng. 2021;194:117–114. https://doi.org/10.1016/j.applthermaleng.2021.117114.
69. AmiriRad E, Davoodi V. Thermo-economic evaluation of a hybrid solar-gas driven and air-cooled absorption chiller integrated with hot water production by a transient modeling. Renew Energy. 2021;163:1253–64. https://doi.org/10.1016/j.renene.2020.08.157.
70. La D, Dai YJ, Li Y, Wang RZ, Ge TS. Technical development of rotary desiccant dehumidification and air conditioning: a review. Renew Sustain Energy Rev. 2010;14:130–47. https://doi.org/10.1016/j.rser.2009.07.016.
71. Fong KF, Chow TT, Lee CK, Lin Z, Chan LS. Advancement of solar desiccant cooling system for building use in subtropical Hong Kong. Energy Build. 2010;42:2386–99. https://doi.org/10.1016/j.applthermaleng.2009.08.008.
72. La D, Dai YJ, Li Y, Ge TS, Wang RZ. Case study and theoretical analysis of a solar driven two-stage rotary desiccant cooling system assisted by vapor compression air-conditioning. Sol Energy. 2011;85:2997–09. https://doi.org/10.1016/j.solener.2011.08.039.
73. Hurdogan E, Buyukalaca O, Yılmaz T, Hepbasli A, Uckan R. Investigation of solar energy utilization in a novel desiccant based air conditioning system. Energy Build. 2012;55:757–64. https://doi.org/10.1016/j.enbuild.2012.02.017.
74. Panaras G, Mathioulakis E, Belessiotis V, Kyriakis N. Theoretical experimental investigation of the performance of a desiccant air-conditioning system. Renew Energy. 2010;35:1368–75. https://doi.org/10.1016/j.renene.2009.11.011.
75. Subramanyam N, Maiya MP, Murthy SS. Application of desiccant wheel to control humidity in air-conditioning systems. Appl Thermal Eng. 2004;24:2777–88. https://doi.org/10.1016/j.applthermaleng.2004.04.008.
76. Li Y, Sumathy K, Dai YJ, Zhong JH, Wang RZ. Experimental study on a hybrid desiccant dehumidification and air conditioning system. J Sol Energy Eng. 2006;128:77–82. https://doi.org/10.1115/1.2148977.

77. Jia CX, Dai YJ, Wu JY, Wang RZ. Analysis on hybrid desiccant air-conditioning system. Appl Thermal Eng. 2006;26:2393–00. https://doi.org/10.1016/j.applthermaleng.2006.02.016.
78. Kanoğlu M, Çarpınlıoğlu MÖ, Yıldırım M. Energy and exergy analyses of an experimental open-cycle desiccant cooling system. Appl Therm Eng. 2004;24(5–6):919–32.
79. Angrisani G, Roselli C, Sasso M. Effect of rotational speed on the performance of a desiccant wheel. Appl Energy. 2013;104:268–75. https://doi.org/10.1016/j.apenergy.2012.10.051.
80. Rush W, Wurm J, Wright L, Ashworth RA. A description of the solar MEC field test installation. ISES Conf. 1975 (Los Angeles).
81. Joudi KA, Madhi SM. An experimental investigation into a solar assisted desiccant-evaporative air-conditioning system. Sol Energy. 1987;39:97–107. https://doi.org/10.1016/j.solener.2017.05.071.
82. San JY, Jiang GD. Modeling and testing of a silica gel packed-bed system. Int J Heat Mass Transf. 1994;37(8):1173–9.
83. Singh S, Singh PP. Regeneration of silica gel in multi-shelf regenerator. Renew Energy. 1998;13:105–19.
84. Techajunta S, Chirarattananon S, Exell RHB. Experiments in a solar simulator on solid desiccant regeneration and air dehumidification for air conditioning in a tropical humid climate. Renew Energy. 1999;17(4):549–68.
85. Ando K, Kodama A. Experimental study on a process design for adsorption desiccant cooling driven with a low-temperature heat. Adsorption. 2005;11:631–6.
86. Azar AAJ, Slayzak S, Judkoff R, Schaffhauser T, DeBlasio R. Performance assessment of a desiccant cooling system in a CHP application incorporating an IC engine. Int J Distrib Energy Resour. 2005;1:163–84.
87. Qin CK, Schmitz G. Engine-driven desiccant-assisted hybrid air-conditioning system. In: Proceedings of the 23rd world gas conference. Amsterdam; 2006.
88. Kohlenbach P, Bongs C, White S, Ward J. Performance modeling of a desiccant-evaporative sorption air conditioning system driven by micro- turbine waste heat in tropical climates. AIRAH sustainability for tropical and sub-tropical climate conference; 2006.
89. Zhuo X, Ding J, Yang X, Chen S, Yang, J. The experimentation system design and experimental study of the air-conditioning by desiccant type using solar energy. In: Proceedings of the sixth international conference for enhanced building operations, vol. 8, Shenzhen, China; 2006.
90. Kabeel AE. Solar powered air conditioning system using rotary honeycomb desiccant wheel. Renew Energy. 2007;32:1842–57.
91. Ge TS, Dai YJ, Wang RZ, Li Y. Experimental investigation on a one rotor two-stage rotary desiccant cooling system. Energy. 2008;33:1807–15.
92. Yilmaz T, Hürdogan E, Büyükalaca O, Hepbasli A. Experimental investigation of a novel desiccant cooling system. Energy Build. 2010;42:2049–60.
93. Ge TS, Ziegler F, Wang RZ, Wang H. Performance comparison between a solar driven rotary desiccant cooling system and conventional vapor compression system (Performance study of desiccant cooling). Appl Therm Eng 2010;0:724–31.
94. Angrisani G, Minichiello F, Roselli C, Sasso M. Experimental investigation to optimise a desiccant HVAC system coupled to a small size cogenerator. Appl Thermal Eng. 2011;31:506–12.
95. Ge F, Guo X, Hu Z, Chu Y. Energy savings potential of a desiccant assisted hybrid air source heat pump system for residential building in hot summer and cold winter zone in China. Energy Build. 2011;43:3521–7.
96. El-Agouz SA, Kabeel AE. Performance of desiccant air conditioning system with geothermal energy under different climatic conditions. Energy Convers Manag. 2014;88:464–75.
97. Ying S, Yufeng Z, Lei F, Jinshe N, Lijun M. Optimization analysis of high temperature heat pump coupling to desiccant wheel air conditioning system. Trans Tianjin Univ. 2014;20:182–8.
98. Angrisani G, Roselli C, Sasso M. Experimental assessment of the energy performance of a hybrid desiccant cooling system and comparison with other air-conditioning technologies. Appl Energy. 2015;138:533–45.
99. Angrisani G, Diglio G, Sasso M, Calise F, Dentice DM. Design of a novel geothermal heating and cooling system: Energy and economic analysis. Energy Convers Manag. 2016;108:144–59.
100. Muthu S, Sekarapandian N. Simulation of hybrid packed desiccant beds for dehumidification and drying. SAE Int J Adv Curr Pract in Mob. 2020;3(2020–28–0019):628–37. https://doi.org/10.4271/2020-28-0019.
101. Muthu S, Sekarapandian N. Simulation of the performance of solar driven thermoelectric based rotary desiccant wheel hvac system. SAE Int J Adv Curr Pract Mob. 2020;3(2020-28-0041):654–60. https://doi.org/10.4271/2020-28-0041.
102. Jani DB, Mishra M, Sahoo PK. Solid desiccant air conditioning: a state of the art review. Renew Sustain Energy Rev. 2016;60:1451–69. https://doi.org/10.1016/j.rser.2016.03.031.
103. Sivasakthivel T, Murugesan K, Thomas HR. Optimization of operating parameters of ground source heat pump system for space heating and cooling by Taguchi method and utility concept. App Energy. 2014;116:76–85. https://doi.org/10.1016/j.apenergy.2013.10.065.
104. Techajunta S, Chirarattananon S, Exell RHB. Experiments in a solar simulator on solid desiccant regeneration and air dehumidification for air conditioning in a tropical humid climate. Renew Energy. 1999;17(4):549–68. https://doi.org/10.1016/S0960-1481(98)00776-9.
105. Ando K, Kodama A. Experimental study on a process design for adsorption desiccant cooling driven with a low-temperature heat. Adsorption. 2005;11:631–6. https://doi.org/10.1007/s10450-005-5997-1.
106. Jani DB, Mishra M, Sahoo PK. Investigations on effect of operational conditions on performance of solid desiccant based hybrid cooling system in hot and humid climate. Therm Sci Eng Prog. 2018;7:76–86. https://doi.org/10.1016/j.tsep.2018.05.005.
107. Verma V, Murugesan K. Experimental study of solar energy storage and space heating using solar assisted ground source heat pump system for Indian climatic conditions. Energy Build. 2017;139:569–77. https://doi.org/10.1016/j.enbuild.2017.01.041.
108. Patel JH, Qureshi MN, Darji PH. Experimental analysis of thermal energy storage by phase change material system for cooling and heating applications. Materials Today: Proc. 2018;5(1):1490–500. https://doi.org/10.1016/j.matpr.2017.11.238.
109. Panchal H, Patel K, Elkelawy M, Bastawissi HA. A use of various phase change materials on the performance of solar still: a review. Int J Amb Energy. 2021;42(13):1575–80. https://doi.org/10.1080/01430750.2019.1594376.
110. Bhabhor KK, Jani DB. Performance analysis of desiccant dehumidifier with different channel geometry using CFD. Journal of Build Eng. 2021;44:103021. https://doi.org/10.1016/j.jobe.2021.103021.
111. Jani DB, Bhabhor K, Dadi M, Doshi S, Jotaniya PV, Ravat H, Bhatt K. A review on use of TRNSYS as simulation tool in performance prediction of desiccant cooling cycle. J Therm Anal Calorim. 2020;140:2011–31. https://doi.org/10.1007/s10973-019-08968-1.
112. Dadi M, Jani DD. TRNSYS simulation of an evacuated tube solar collector and parabolic trough solar collector for hot climate of Ahmedabad. Available at SSRN 3367102. 2019. https://doi.org/10.2139/ssrn.3367102.

113. Jani DB. An overview on desiccant assisted evaporative cooling in hot and humid climates. Algerian J Eng Technol. 2019;1:1–7. https://doi.org/10.5281/zenodo.3515477.
114. Jani DB, Mishra M, Sahoo PK. Solar assisted solid desiccant—vapor compression hybrid air-conditioning system. Appl Solar Energy. 2018:233–50. https://doi.org/10.1007/978-981-10-7206-2_12.
115. Gao Z, Mei VC, Tomlinson JJ. Theoretical analysis of dehumidification process in a desiccant wheel. Heat Mass Transf. 2005;41:1033–42. https://doi.org/10.1007/s00231-005-0663-4.
116. Muthu S, Talukdar P, Jain S. Effect of regeneration section angle on the performance of a rotary desiccant wheel. Journal of therm sci and eng app. 2016;8(1):011013. https://doi.org/10.1115/1.4030966.
117. Sheng Y, Zhang Y, Fang L, Nie J, Ma L. Optimization analysis of high temperature heat pump coupling to desiccant wheel air conditioning system. Trans Tianjin Univ. 2014;20:182–8. https://doi.org/10.1016/j.energy.2015.02.068.

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