Solar Energy as a Regeneration Heat Source in Hybrid Solid Desiccant – Vapor Compression Cooling System – A Review

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Abstract: A critical review on solar assisted hybrid solid desiccant – vapor compression air conditioning system has been carried out. This article delivers information on basics principles of solid desiccant vapor compression air conditioning system powered by solar energy as well as recent researched in air-conditioning and built environment produced by use of hybrid cooling. Solar energy can be used as a source for regeneration heat provided in reactivating desiccant dehumidifier used in alternate cooling systems. Solid desiccant dehumidification system coupled with vapor compression-based hybrid air-conditioning systems can successfully assisted by renewable solar thermal energy to dampen electricity use and to conserve environment in place of conventional air-conditioning. The feasibility and energy saving potential of solar powered desiccant cooling systems is illustrated and discussed as compared to the conventional vapor compression-based air conditioning systems.
It is found that the solid desiccant integrated hybrid cooling systems are feasible and favourable than the traditional vapor compression air conditioning or space cooling system, because it is better sense for cost-effective and cleaner air-conditioning. The present critical review can enrich the worth of solar energy as renewable regeneration heat source in solid desiccant-based hybrid cooling system and helps to guide future researchers to take the research opportunities in this area.

***Keywords*—Solar Energy, Solid Desiccant, Regeneration, TRNSYS, Desiccant Wheel.**

I. INTRODCUTION

Now a days an innovative approach in the field of space cooling application has been introduced as a hybrid Solid desiccant and vapor compression refrigeration system to overcome environment and economics issue due to maximum use of standalone vapor compression air condition system. Solar thermal energy is feasible to reduce electrical power in hybrid air-conditioning system which can improves indoor room environment. In hybrid cooling, optimal air-conditioning would result as vapor-compression system performs only cooling operations while desiccant dehumidification system takes care of humidity control. Thus, in desiccant assisted hybrid cooling system both sensible and latent loads are handled separately and effectively. So, the desiccant based hybrid cooling can control temperature and humidity of cooling air independently.

This type of hybrid cooling neglects the requirement of low dew point temperature of evaporator cooling coil and subsequently post-reheating in Vapor compression refrigeration cooling unit. It also alleviates the condensation of air while cooling when outdoor humidity rises. Its operating costs saved substantially by the use of freely available solar energy for regenerating the desiccant wheel. The greatest cooling requirement in building during the summer season is also associated with availability of intense solar radiation provides an excellent opportunity to use of freely available renewable solar energy to integrate with desiccant based hybrid air-conditioning. Thus, desiccant assisted space cooling can meet the demands of thermal comfort, economy, energy conservation and environmental protection.

Solar energy for cooling has not having wide background for commercial application. Lamp and Ziegler (1998) had started research on air conditioning assisted by solar energy up to 1996. Various experiments on the cost-effective feasibility in air-conditioning powered by solar energy were conducted Tsoutsos et al. (2003). Various studies of space cooling technologies powered by solar energy had conducted by Karagiorgas et al. (2018) for identification of different configurations of solar thermal systems in house hold and commercial applications.

In the critical review, basic working principles of solar assisted desiccant-based hybrid cooling system has been described. Recent researches related to desiccant based cooling system has also been discussed. Investigations in the field of solar assisted desiccant-based hybrid cooling cycles were summarised which is related to novel reactivating methods. The solid desiccant-based rotary desiccant wheel can be regenerated by use of solar energy to enhance overall system performance.
The motive behind this critical review is to evaluate an optimal use of solar heat energy to provide regenerative heat source for regenerating desiccant wheel used in hybrid solid desiccant and vapor compression cooling system. The motivation in the solar assisted desiccant-based hybrid cooling systems are economically viable in case of using freely available renewable solar heat energy (Syed et al. 2004), sustainable and environmentally friendly space cooling systems.

II. PRINCIPLE OF SOLAR ASSISTED HYBRID SOLID DESICCANT – VAPOR COMPRESSION COOLING SYSTEM

In solar powered solid desiccant and vapor compression hybrid space cooling system, solid desiccant dehumidification system controls only the moisture content of the supply air (latent load) while traditional vapor compression system sensibly cools (sensible load) the conditioned supply room air. Moreover, the use of desiccant wheel introduces some minor parasitic sensible load as it increases the dry bulb temperature while dehumidifying the moisture laden process air (D.B. Jani et al. 2016). Solar powered solid desiccant – vapor compression hybrid air-conditioning system working on principle of adsorption of moisture (J.C. Sheridan et al. 1985).

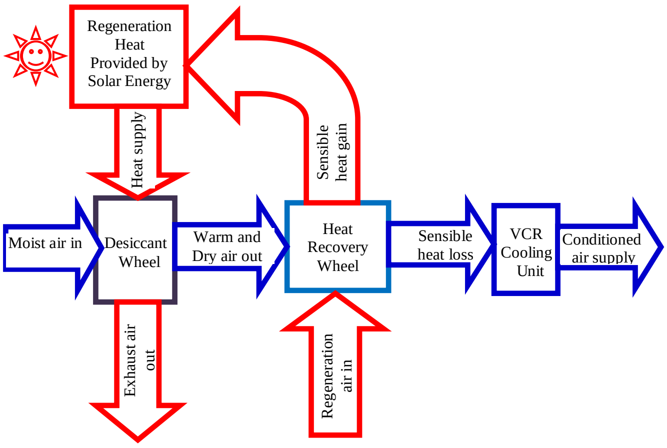

Fig 1 Principle of Solar Assisted Hybrid Solid Desiccant – Vapor Compression Cooling (J.C. Sheridan et al. 1985).

In its operation, moisture laden ventilated or recirculated air is first passes through channels of rotary dehumidifier so that the water vapor presented in it is adsorbed by a rotating desiccant dehumidifier due to the pressure difference between them. During the process of dehumidification, adsorption heat increases the temperature of process air at dehumidifier exit. The dehumidifier process air available at outlet of dehumidifier cools up to the desired room supply conditions by combined effort of heat recovery wheel and vapor compression cooling coil. The cycle runs continuously by regenerating the desiccant wheel by driving off moisture with help of supplying hot reactivation air. This is achieved by heating the desiccant material to its temperature of reactivation which mainly depends on the type of the desiccant used in matrix channel. Thermal energy needed for regenerating the rotary dehumidifier is made available by use of solar thermal collector. A desiccant based hybrid air-conditioning system, consists of mainly four components, namely the reactivation air heater, the rotary dehumidifier, heat recovery wheel and the traditional vapor compression cooling unit (Fig. 1). As per the type/nature of desiccant materials used and intensity of solar radiations available to achieve the required regeneration temperature of desiccants used, different configurations and description of the system is possible as follows (D.B. Jani et al. 2016).

III. WORKING OF SOLAR ASSISTED HYBRID SOLID DESICCANT – VAPOR COMPRESSION COOLING SYSTEM

The integrated form of the solar powered solid desiccant – vapor compression hybrid air-conditioning commonly known as ventilation system while it makes use of fresh ventilated (outdoor) air as a process air at the dehumidifier inlet. In ventilation mode, outdoor fresh air is used as process air at dehumidifier inlet. In the process air side of the system configuration shown in Fig. 2 (J.J. Jurinak, 1982), the fresh ambient air stream (state 6) passes through various channels of rotary desiccant wheel. Its humidity is substantially lowered by the desiccant material owing to pressure difference between it and the vapor in air can be said and the heat of adsorption increases its temperature so that a dehumidified warm air stream exiting the dehumidifier (state 2). Then it is cooled successively in the heat recovery wheel (2–3), and later in vapor compression cooling coil (3–4) up to the room supply designed comfort conditions. Existing condition (state 5) within conditioned space is also shown [8]. In regeneration side, room return air (state 1) is sensibly heated by passing through heat recovery wheel, simultaneously its pre-cools pas- sing process air on the other side. This is necessary to reduce the re- generation heat consumption. So, the temperature of reactivation air is elevated while coming out from the heat recovery wheel while the humidity ratio is constant (state 7). This heated air is finally reached its reactivation temperature (state 8) by passing through liquid to air heating coil for reactivating the desiccant material used in the dehumidifier. The hot and humidified air available after the regeneration process at dehumidifier exit (state 9) is exhausted to the ambient (D.B. Jani et al, 2018).

In case of recirculation mode as shown in Fig. 3 (J.J. Jurinak, 1982), return room air which is generally available at lower temperature and humidity as compared to the outdoor condition is used as process air at dehumidifier inlet. In particular cases, air is not 100% recirculated all the time due to needs of fresh air intake to satisfy indoor air quality is called mixed mode, a fraction is fresh air mixed with recirculated air (D.B. Jani et al, 2018).

The most important component of hybrid Solid Desiccant Vapor Compression Refrigeration system is Desiccant wheel. It is a driving system having a motor powered by electricity, wheel disc and belt to rotate wheel. Important parameters of desiccant wheel are shown in Table I.

Table 1. Desiccant wheel parameters (D.B. Jani et al, 2016).

Parameters	Value
Diameter	360 mm
Width	100 mm
Channel Shape	Sinusoidal
Desiccant Material	Synthesized Metal Silicate
Rotational speed of desiccant wheel	20 revolution per hour
Desorption temperature of desiccant material	80 -140 ˚C
Adsorption area / desorption area	3:1

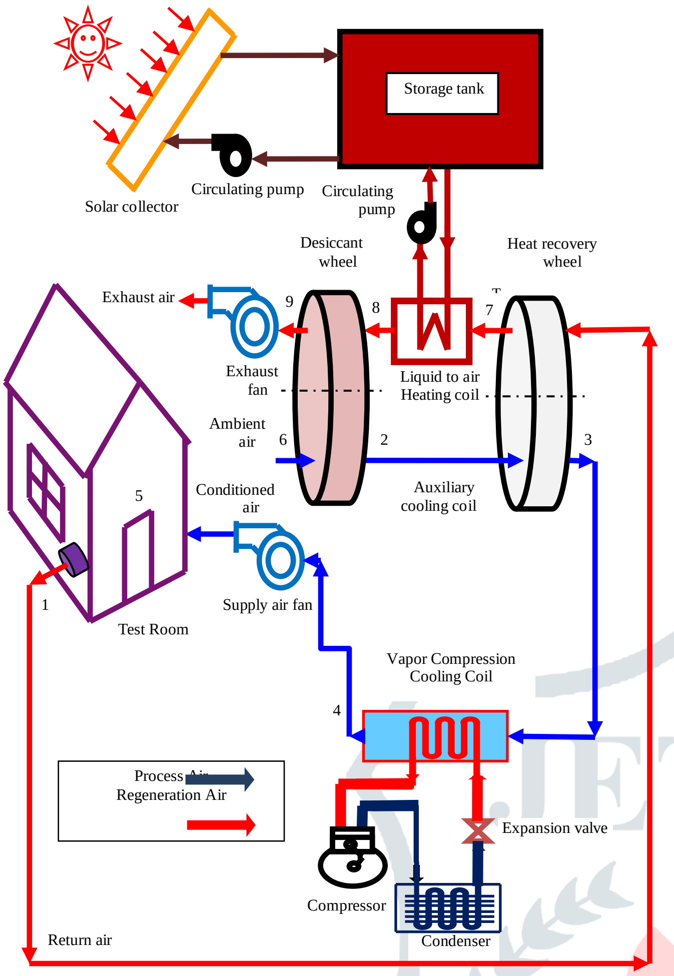

Fig 2 Solar Assisted hybrid solid desiccant – vapor compression cooling system in ventilation mode (J.J. Jurinak 1982)

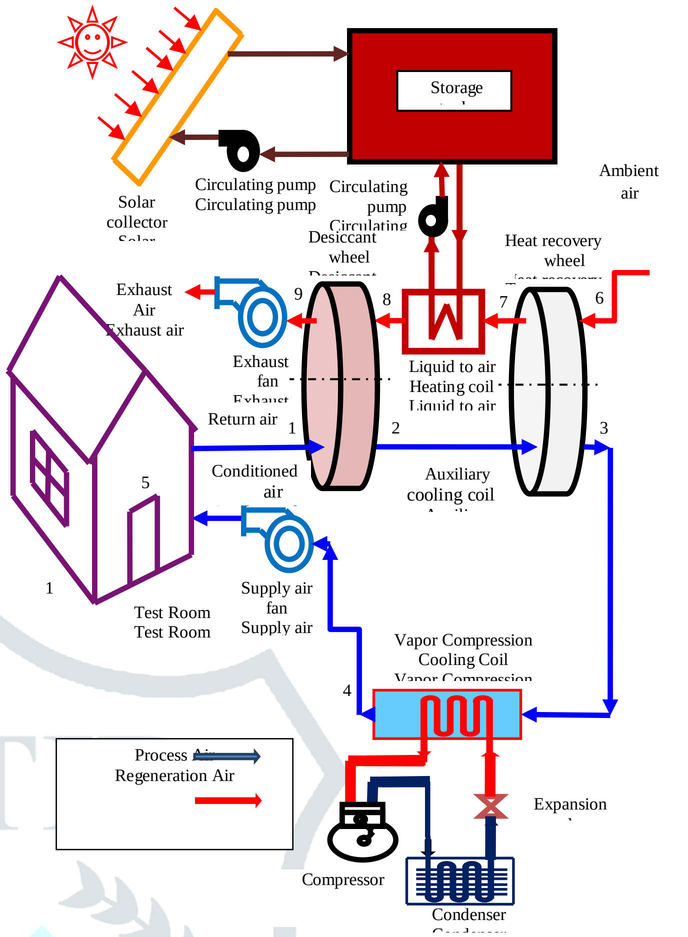

Fig 3 Solar Assisted hybrid solid desiccant – vapor compression cooling system in recirculation mode (J.J. Jurinak 1982)

Commonly used desiccant materials, regeneration temperatures and regeneration heat sources are tabulated in table II.

Table 2. Desiccant material along with regeneration temperature and heat source [10-19].

Desiccant Material	**Regeneration Temperature (ºC)**	**Regeneration Heat Source**
Zeolite	> 150	Electric
FAM-Z01 polymer	50–80	Electric, Thermal
FAM zeolite material	50–80	Electric, Thermal
Super adsorbent polymer (SAP)	50–80	Electric, Thermal
Polymer desiccant	30–60	Electric
super desiccant polymer (SDP)	30–60	Thermal
Activated carbon	100–150	Thermal
Silica gel	70–100	Thermal, Waste heat, Solar energy
Lithium chloride	40–70	Solar, Waste heat
titanium silicate	55–85	Solar, Waste heat
Activated alumina	80–100	Solar, Waste heat

IV. PREVIOUS RESEARCH ON SOLAR ASSISTED HYBRID SOLID DESICCANT – VAPOR COMPRESSION COOLING SYSTEM

Khalid and Madhi (1987) investigated a solar assisted open adsorption cooling system. Various experiments are carried out at different reactivation temperature on desiccant wheel having silica gel as a desiccant material. It is found that the rise in reactivation temperature and mass flow rate can ameliorate overall performance of the system. Bourdoukan et al. (2007) had simulated the performance of solar assisted desiccant cooling systems coupled with direct flow vacuum tube collectors. It is found that vacuum tube collectors have a great potential in solar desiccant cooling operating with a global efficiency of 0.55 for a regeneration temperature of 60 °C. It is found that for increasing the reactivation temperature up to 12 °C in required regeneration temperature, the global efficiency of the system is reduced by 45%. Solar assisted desiccant wheel cycle of different operating modes was proposed by Vitte et al. (2008). It is found Savings of 39% were obtained compared with existing vapor compression air condition system.

Maalouf et al. (2005) experimentally investigated Li-Cl dehumidifier integrated with solar liquid collectors to study the effect of regeneration temperature on system performance. It is found that decrease in air change hours during in occupation period lowers the required reactivation heat supply hours of approximately 40%. Kim and Ferreira (2008) conducted a state of art review on various application of the solar energy for space cooling techniques like thermo mechanical, absorption, adsorption and desiccant solutions. If a 10% efficiency solar panel is combined with a vapor compression air conditioner with 3.0 COP, the overall efficiency will be 30%. Assuming the unit price of the solar panel is €5/Wp, the solar panel alone would cost ca. €1700 to produce 333W electricity for 1 kW cooling. Fong et al. (2010) simulated different configurations of solar powered desiccant cooling systems using TRNSYS. Energy savings by use of hybrid cooling designs were up to 35.2% when compared to conventional centralized air conditioners. Halliday et al. (2002) investigated experimental study on desiccant cooling system assisted solar heat energy. In the system solar energy makes use of 72% of it's the thermal energy for regenerating the desiccant wheel. It is found that the solar heating coils in summer time can save energy for regeneration air heating and process air cooling up to 39%. Solar assisted desiccant cooling system was investigated experimentally Bourdoukan et al. (2009). Coefficient of performance (COP) was evaluated as 4.2 on basis of electrical energy input by conducting different experiments on system. While COP calculated based on primary energy consumption based on solar installations was 0.45. Solar powered desiccant – vapor compression hybrid space cooling system was simulated by Yadav (1995). It is found that when the latent load constitutes 90% of the total cooling load, the system can generate up to 80% of energy savings as compared to vapor compression based conventional cooling system. Kabeel (2007) experimentally evaluated the performance of a hybrid desiccant air-conditioning system integrated with a rotary honeycomb wheel that utilized renewable solar energy for the reactivation, at various conditions of inlet air and different radiation intensity of solar heat. The obtained results showed that the system was found economical in the regeneration process by use of solar energy for all flow rates compared with the absorption process. Fong et al. (2011) simulated solar assisted solid desiccant-based hybrid cooling system to evaluate indoor air quality. It is found that the desiccant dehumidifier used in the hybrid cooling system was regenerated by use of solar energy to achieve greater energy savings. Lafuenti et al. (2012) was simulated thermodynamic performance of the solar assisted desiccant-based comfort cooling system Efficiency of the hybrid cooling system was predicted in the range of 0.176–0.75. Baniyounes et al. (2012) simulated performance of the solar assisted desiccant-based cooling system using TRNSYS simulation tool. The economic viability of the system was evaluated for the annual cooling load 6428 kWh. Substantial saving in high grade electrical energy was achieved by the use of renewable solar heat for reactivation of desiccant dehumidifier.

Al-Alili et al. (2012) proposed the use of a concentrated PVT solar collector to drive a solid desiccant cooling (SDC) integrated to a VCC. The collector thermal output was used to reactivate the desiccant wheel, whereas the electrical output was used to drive the VCC. The complete system was modelled using TRNSYS and Abu Dhabi weather conditions. In addition, the system performance was compared to a VCC powered by PV panels and a solar absorption cycle. The simulation results indicate that the average COP of the proposed cycle, VCC assisted by PV panels, and solar absorption-based cooling cycle was 0.68, 0.34 and 0.29, respectively.

Sheridan and Mitchell (1985) simulated solar powered hybrid desiccant cooling system using TRNSYS. Renewable solar heat is used in cycle to regenerate the desiccant dehumidifier. The performance of the system was determined for different loads and climatic conditions. It is found that the hybrid system saves more energy as compared to traditional vapor compression system when the load to be met has a high latent fraction. Ahmed et al. (2005) conducted study of solar assisted desiccant wheel by use of optimization and found that 73% of the regeneration heat energy required can be share by solar air heater. La et al. (2011) done experimental tests on solar powered two stage desiccant-based hybrid space cooling system. The performance of the system is also simulated by use of TRNSYS. The COP of system 0.95 was evaluated on the basis of primary energy supply and 31% electrical power was saved as compared to the conventional vapor compression air-conditioning system.

Khalid et al. (2009) conducted experimental study on solar powered pre-cooled hybrid desiccant cooling system for comfort space cooling. The model was simulated by use of TRNSYS. Payback period and life cycle assessment were performed for evacuated tube solar thermal collectors. La et al. (2011) experimentally investigated the performance of a two-stage desiccant cooling system combined with a traditional vapor compression air-conditioner. The solar collector was used for regeneration heat. Using TRNSYS simulation tool, the system performance was investigated under hot & humid weather conditions. The power consumption was reduced up to 36%. Sukamongkol et al. (2010) experimentally regenerated the desiccant wheel using the waste heat of heat and a Photo voltaic thermal air collector. It was found saving of 19% on the energy use of the cooling system. Solar powered solid desiccant-based cooling system was simulated by La et al. (2011) using TRNSYS. Substantial energy savings can be achieved by use of solar heat for regenerating the desiccant wheel.

The COP defined for the different configuration was based on primary energy consumption for the solar energy utilization were summarised in the following Table III.

Table III. Experimental work on hybrid vapor compression - solid desiccant air conditioning systems assisted by solar energy

Researcher	**Solar Collector**	**Working Fluid**	**Area of Solar Collector (m^2)**	**COP**
Li et al. (2006)	Photo Voltaic Thermal Solar Collector	Air	100	0.510
Whute et al. (2009)	Flat Plate Collector	Water	101	0510
Enteria et al. (2010)	Flat Plate Collector	Water	10	0.242
Agyenim (2010)	Vacuum tube water	Water	12	0.561
Hidalgo et al. (2008)	Flat Plate COllector	Water	50	2.47
Bujedo et al. (2011)	Evacuated Tube Collector + Flat Plate Collector	-	40+38.5	-
Mammoli et al. (2010)	Evacuated Tube Collector + Flat Plate Collector	-	228	0.619

Davanagere et al. (2015) simulated simulation of solar assisted hybrid solid desiccant – vapor compression air-conditioning system. It was found that the operational cost of the hybrid system reduced significantly when solar energy used for regeneration of desiccant wheel.

V. CONCLUSION

Hybrid solid desiccant – vapor compression air conditioning system powered by solar energy is relatively feasible and advance air conditioning system which can be used as an alternative of conventional vapor compression air conditioning system in hot and humid weather condition as solar energy can lead to energy saving in range 40–45%.

In the present critical review, the basic principles and work done by different researchers on application of solar energy in hybrid solid desiccant – vapor compression air conditioning system as well as various desiccant materials and its regeneration temperature has been summarised.

It is found that the solar assisted hybrid solid air-conditioning has a strong potential for significant primary energy savings as regeneration of desiccant wheel can be done. Thus, if economic factors taken into consideration, the application of freely available renewable solar energy for desiccant regeneration in hybrid air conditioning or space cooling technology would be more feasible and beneficial. Desiccant based hybrid space cooling techniques is economically sustainable, and environmentally more feasible for high outdoor humidity or hot and humid summer weather conditions.

By making the direction of future research on space cooling towards solar powered solid desiccant – vapor compression hybrid space cooling augmenting the contribution of solar assisted desiccant-based hybrid cooling which can bring to the amelioration of comfort, energy and cost savings.

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