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Renewable and Sustainable Air Conditioning

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Abstract

The simultaneous control of air temperature and humidity are the main functions of an air conditioner in order to provide human thermal comfort conditions. The conventional vapor compression air conditioning system cools the air below its dew point temperature to remove the moisture from the air. In hot and humid regions, considerable amount of energy is used for moisture removal using these systems. Because of the high energy cost of conventional systems and poor control of latent load, need arises for some alternative cooling devices. In this chapter alternative and renewable based air conditioning systems are described to overcome the increasing use of primary energy by conventional air conditioning systems. Desiccant cooling is found to be a suitable alternative to these cooling systems. The configurations of desiccant cooling systems to achieve better performance are described. Furthermore, a comparative analysis of desiccant cooling system operating on ventilation and recirculation cycle has been presented. The results showed the system operating under the ventilation cycle has a better coefficient of performance as compared to the recirculation cycle because of the less input/regeneration heat required. The desiccant cooling technology is both cost-effective and environmental friendly as no refrigerant is used in these systems.

Keywords: renewable based cooling, sustainability, energy efficient, desiccants, evaporative cooler

1. Introduction

The increasing population, technological advancements, and materialistic living standards have significantly increased the energy demand for cooling devices in last few decades. Almost 15% of world's total energy is consumed by air conditioning systems. The human thermal comfort conditions are described in terms of efficient control of sensible and latent load. The basic function of an air conditioner is to simultaneously control temperature,

humidity, and quality of supply air as shown in **Figure 1**. Generally, in order to provide thermal comfort conditions to the occupants, an air conditioning system should maintain indoor air temperature of 18–26°C and relative humidity of 40–70%. The accurate and effective control of humidity becomes more crucial for applications where less moist environment is required.

The term sensible heat ratio is used to determine the performance of an air conditioner in terms of its ability to control sensible and latent load. Smaller the value of sensible heat ratio larger is the value of latent cooling loads. The value of sensible heat ratio is about 0.75 for the commonly used conventional vapor compression air conditioning system. The vapor compression air conditioning system controls the latent load by condensation process. The air is cooled below its dew point temperature to remove the moisture and then reheated again to desired supply temperature. A considerable amount of energy is wasted during this process of overcooling and reheating which lowers the system overall coefficient of performance. Moreover process of condensation creates an environment for the growth of harmful fungi and bacteria. Because of the high energy cost of these conventional systems and poor control of latent load, need arises for some alternative cooling devices.

To avoid the excessive waste of energy, an alternative way to achieve desired moisture reduction is the use of desiccant dehumidification system in which a desiccant material absorbs moisture from the humid air. Thermal energy is used to regenerate the desiccant material and cycle continues. The system is both cost-effective as well as environmental friendly. Since no refrigerant is used in these systems so depletion of ozone layer is minimized. Low-temperature heat sources, like waste heat from engine or solar heat, can be used to operate the system.

A good desiccant should have better moisture absorption capability and lower temperature of regeneration. Different types of new desiccant materials with high dehumidification performance have been proposed in past few years. These materials have the potential to improve

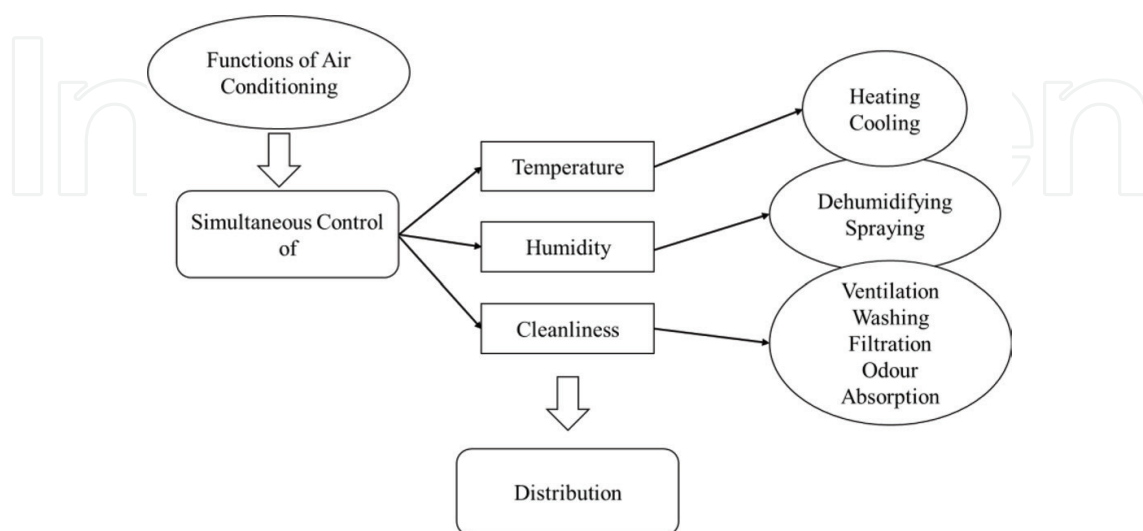


Figure 1. The basic functions of an air conditioner.

the performance of liquid desiccant cooling systems because of lower heat input required for its regeneration. The desiccant cooling system can either be solid or liquid depending upon the type of desiccant material used. Liquid desiccants have advantage over the solid desiccants that these only requires low-temperature heat source to drive the system. The available configurations of the desiccant cooling system are shown in **Figure 2** [1].

The development of desiccant-based cooling technology is a topic of interest now a day and has been widely investigated. Most recently, Rafique et al. [2] investigated the thermal and exergetic performance of a newly developed absorption type desiccant dehumidifier. The aim of this study was to lower the required regeneration temperature by employing liquid desiccant instead of solid desiccant materials. The computed results show that better supply air conditions can be obtained to provide human comfort in the hot and humid climate with effectiveness of the system largely dependent on air flow rate, wheel width, and humidity ratio of the process air. The annual average value of dehumidification performance is found to be 0.55 which shows that system can control the latent load efficiently throughout the year. In another study, Rafique et al. [3] studied the performance of desiccant assisted cooling system for five different sites in Saudi Arabia. The coefficient of performance (COP) of the system was observed to vary from 0.275 to 0.476 for different locations. Kabeel et al. [4] the performances of a solar energy assisted desiccant air conditioning system with different types of storage materials are numerically investigated.

In other studies the development of new configurations [4, 5], parametric and statistical analysis [6, 7], second law and anergy analysis [7, 8], exergoeconomy [9] and different other advancements [10] for desiccant cooling systems have been studied. The desiccant-based technology is on path of development but still a lot of work needs to be done in order to

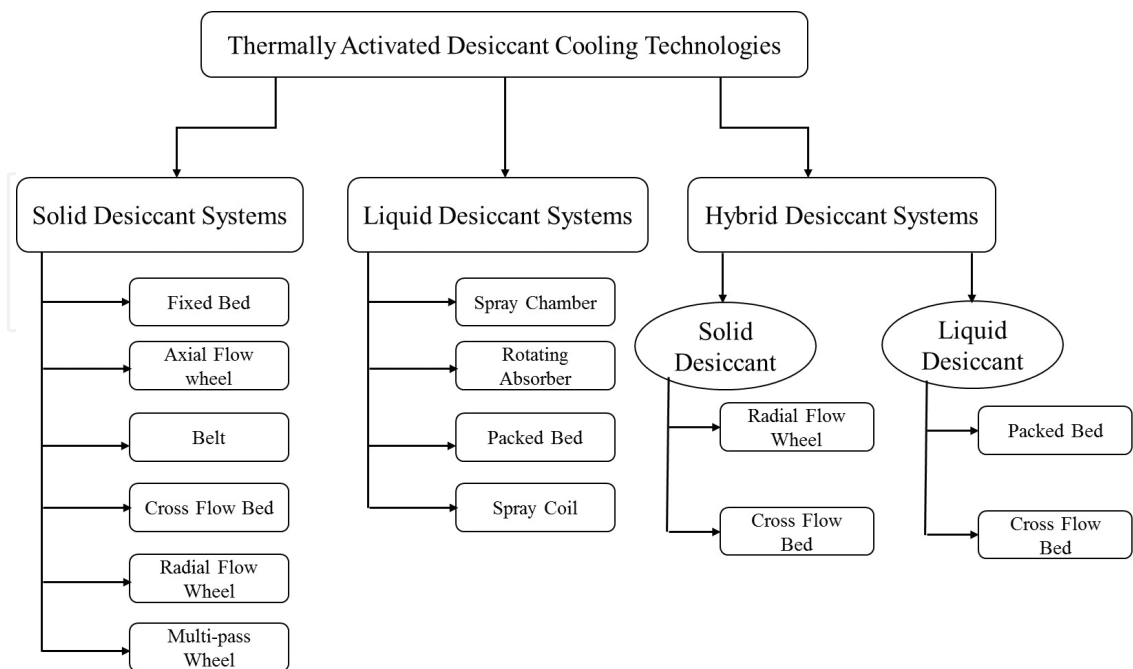


Figure 2. Different configurations for various desiccant systems [1].

make this technology with market friendly. In this regard, the major aim of this chapter is to introduce with the concept of alternative cooling technology, its need and recent developments. Different cooling cycles which can be employed for better performance of the system have been described in this chapter. Based on the developed mathematical model, a comparison has been made between two different configurations of desiccant cooling system.

2. Need of renewable based technology

The use of renewable energy is gaining attention and lot of work still need to be done for different technologies. The overall world energy consumption is presented in **Figure 3**. The increasing use of fossil fuels not only causing fast depletion of energy sources but also causes emitting harmful gases which directly affects the human life. A summary of direct and indirect effects of climatic changes due to burning of these fossil fuels are illustrated in **Figure 4** [11]. Understanding the above mentioned hidden impacts of fossil fuels is critical for evaluating the true cost of fossil fuels—and for promoting our choices for future energy production. These hidden costs must be considered while comparing feasibility of clean energy sources.

Furthermore, major part of the primary energy consumed in the building is accounted for cooling or heating. With regard to the use of energy consumption for HVAC technology, its demand is increasing rapidly, as shown in **Figure 5** [1]. This increasing use of HVAC technology encourages developing alternative cooling technologies which can efficiently utilize renewable energy for its operation.

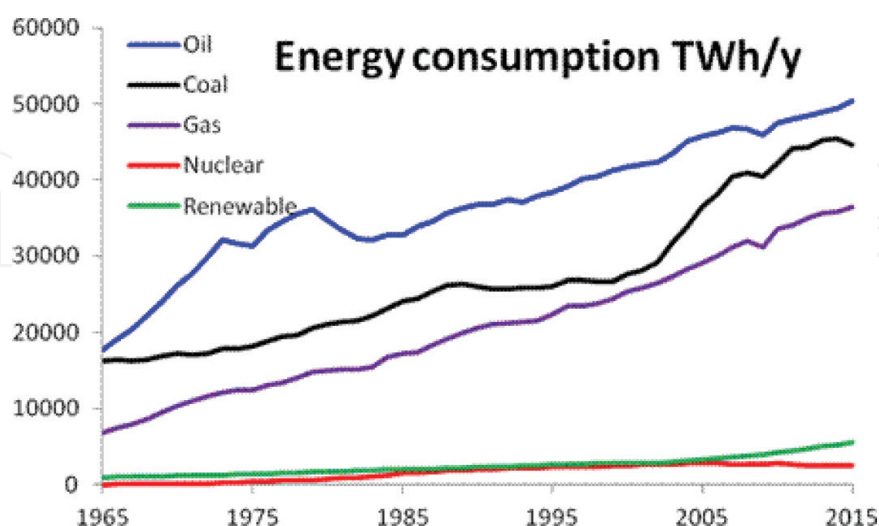


Figure 3. The world's energy consumption according to data of 2015. Source: BP statistical review of world energy 2016.

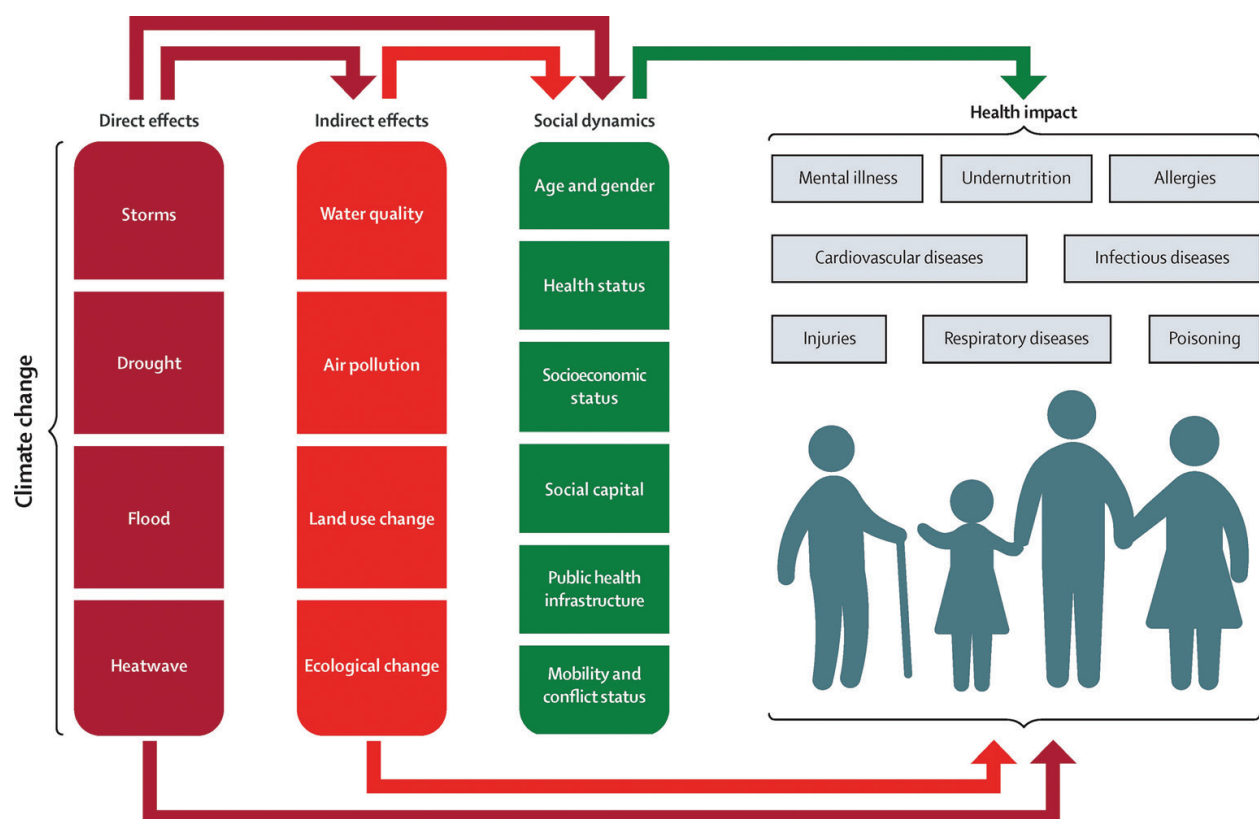


Figure 4. Direct and indirect effects of climate change on public health [11].

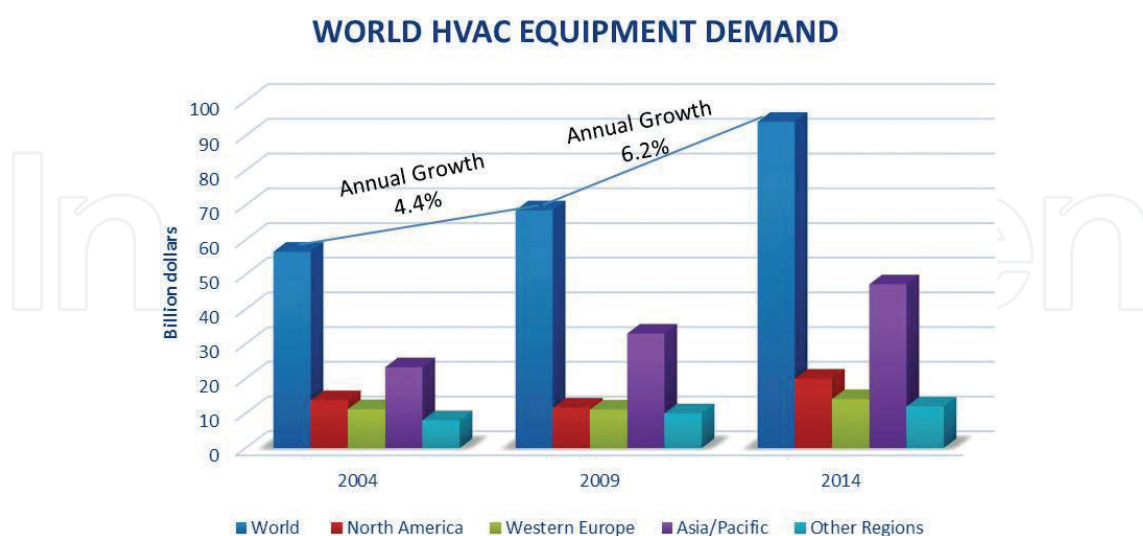


Figure 5. HVAC equipment demand and annual growth. Source: The Freedonia group, Inc. world HVAC equipment demand, Cleveland, OH, USA.

3. System description

The cooling needs for thermal comfort and sunshine timings follow the same pattern. The demand of air conditioning is higher in summer when the sun shines with higher intensity. What if this intensity of sun can be used as an input energy source for the cooling devices?

The issues related to conventional air conditioning technology can be addressed using a new technology called desiccant-based evaporative cooling. This technology is a combination of a desiccant dehumidifier and an evaporative cooler. The schematic representation of desiccant cooling system is shown in **Figure 6** [1]. In such systems, the energy is required to drive the fans, operate the water pump, and to regenerate the desiccant dehumidifier. The required energy can be provided using solar thermal collector for desiccant dehumidifier and photovoltaic modules to drive the fans and the water pump according to the load requirements. The desiccant dehumidifier controls the latent load whereas; evaporative cooler controls the sensible load. Heat recovery medium is used to make the system more energy efficient. For the continuous operation of the system, the regeneration air is heated up to the required regeneration temperature using a solar thermal collector to regenerate the desiccant dehumidifier. The load demand and sunshine follows the same profile which makes this system an effective alternative to conventional air conditioning system. The energy demands for continuous operation of this system can be fulfilled using solar heat according to the load profile.

The use of desiccant cooling technology reduces the energy consumption substantially because of no overcooling and reheating of supply air for moisture removal. More research

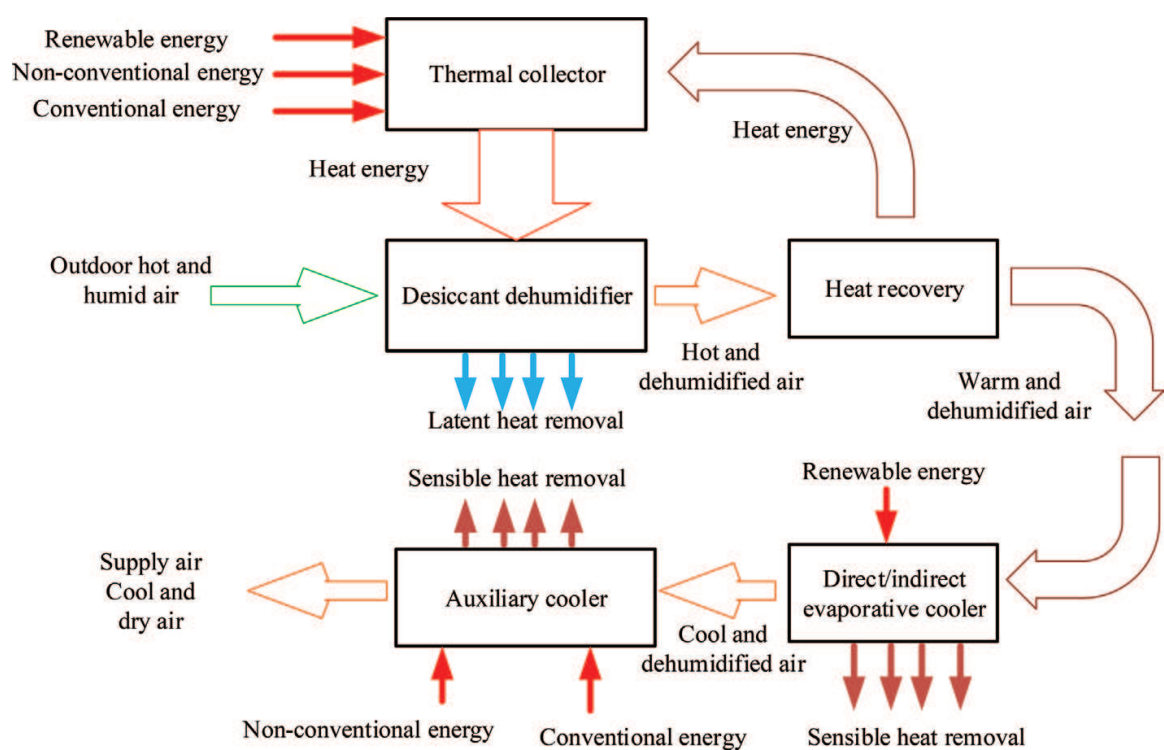


Figure 6. Principle of desiccant-based evaporative cooling technology [1].

should be conducted on innovative design of this technology taking into consideration the associated investment costs. The development of technology is in progress and it is attaining stability in the market. It appears to be reliable, safe, and environmental friendly system according to the needs of our society. This technology needs to be developed and more attention is required for its implementation and promotion.

4. Desiccant cooling cycles

Desiccant cooling is used as an alternative to conventional cooling system. These systems operate without the use of any refrigerant and control the latent as well as sensible load independently which helps in better control of moisture and improve air quality. Thermal energy required for regeneration of these units can be supplied from different heat sources such as solar, biomass, waste heat, etc.

Desiccant technology is a cooling technology which removes moisture from air by a process known as sorption (adsorption or absorption). Different desiccant materials are used for this process. Due to vapor pressure difference, adsorption material absorbs the water vapors from the air. To repeat the cycle continuously, moisture from the desiccant wheel is removed using thermal energy. Basic operating cycles of solid and liquid desiccant cooling are illustrated in **Figure 7** [12] and **Figure 8** [13], respectively. In both cooling systems, desiccant dehumidifier is the major component which controls the latent load followed by an additional cooling system i.e. evaporative cooler. Input heat is provided through some thermal energy medium

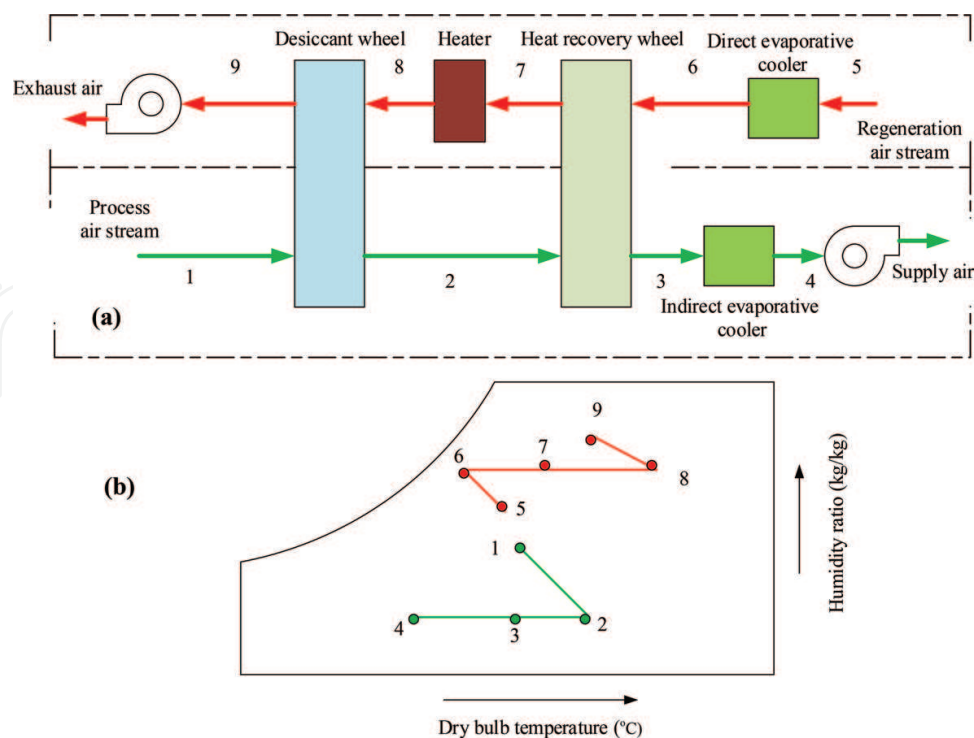


Figure 7. (a) Systematic solid desiccant cooling system with evaporative cooler (b) psychrometric processes [12].

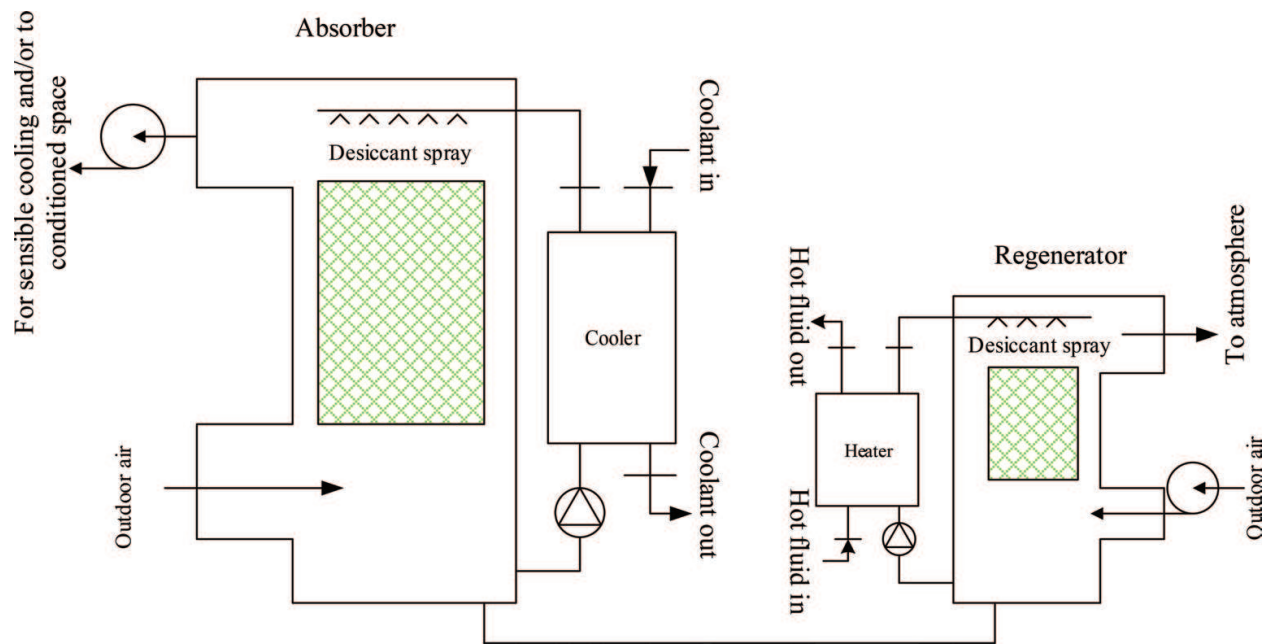


Figure 8. Basic configuration of liquid desiccant system [13].

for desorption of desiccant dehumidifier and continuous operation of the cycle. There are different modifications to the basic desiccant cooling cycles. A summary of different desiccant cooling cycles is:

- **Ventilation cycle:** In this cycle outdoor air is cooled and 100% return air from the conditioned room is utilized for regeneration process. The air leaving at point E is cooled in an evaporative cooler and is used as cold-sink for room return air as shown in **Figure 9**. The room return air is heated in a heat exchanger and then further heated using a heating medium up to a desired regeneration temperature.
- **Recirculation cycle:** this cycle comprises of the same components as ventilation cycle except 100% return air from the conditioned room is mixed with the process air stream at the inlet of desiccant wheel as illustrated in **Figure 10**. This cycle has a Thermodynamic advantage that it can process the air with greater availability for cooling. But this cycle has a higher cold-sink temperature as compared to the ventilation cycle.
- **Dunkle cycle:** This cycle is an effort to combine the thermodynamic advantages of both the ventilation and recirculation cycles. It is a recirculation cycle with an additional heat exchanger to improve the performance of the system. The cycle is shown in **Figure 11**.
- **Recirculation ventilated cycle:** Recirculation ventilated cycle is mix of ventilation and recirculation cycle in which 10% ventilation air mixed with the return air.
- **Wet-surface heat exchanger (WSHE):** The other desiccant cooling cycle make use of a wet-surface heat exchanger (WSHE), wherein the incoming air can be cooled to its dew point temperature. In WSHE, water indirectly cools the process air and then this air is used to cool the return air from the room.

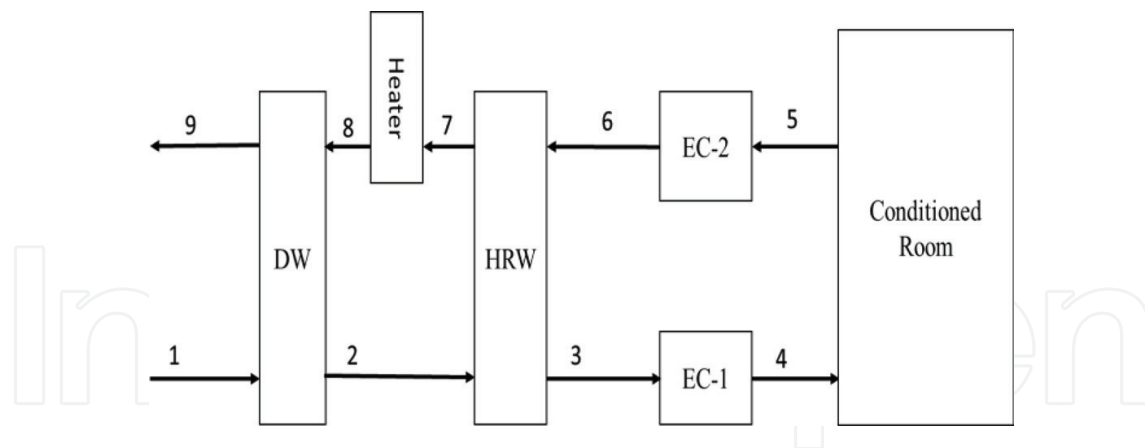


Figure 9. Desiccant evaporative cooling system operating on ventilation cycle.

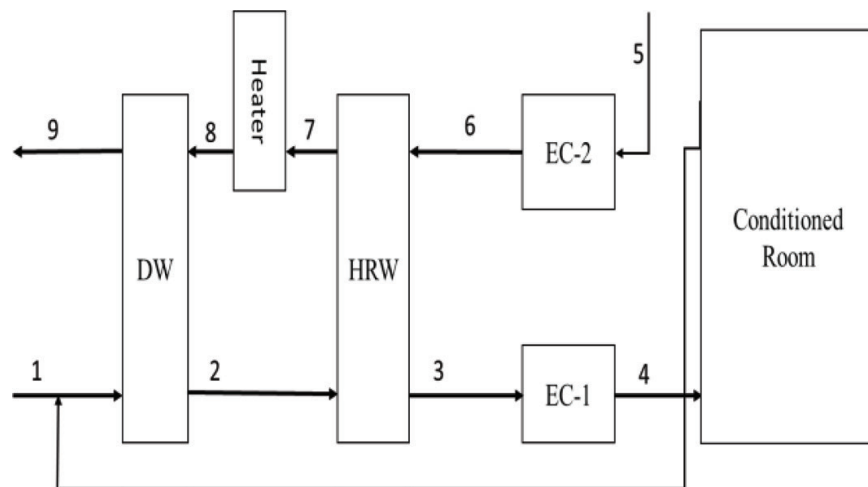


Figure 10. Desiccant evaporative cooling system operating on recirculation cycle.

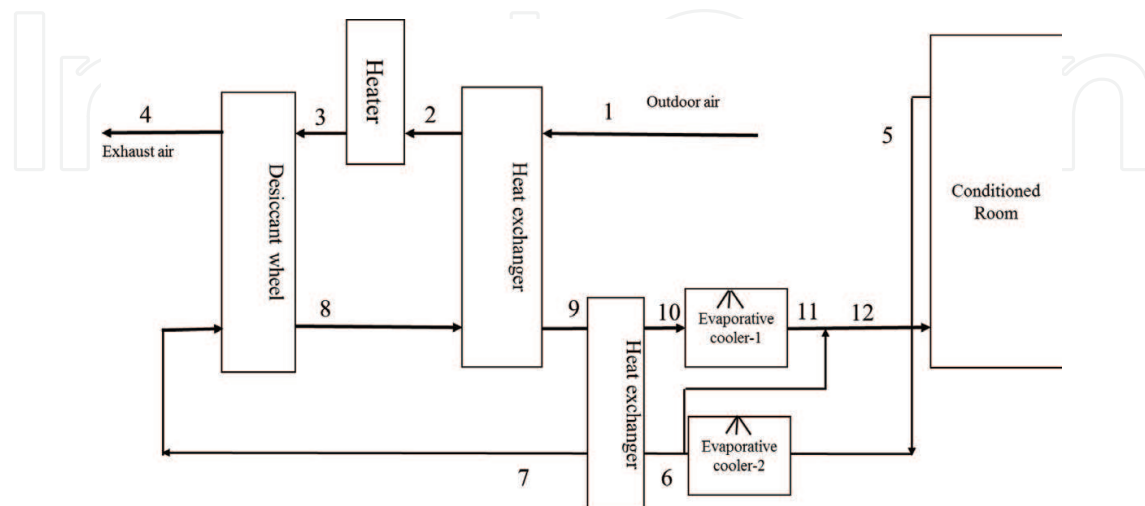


Figure 11. Desiccant evaporative cooling system operating on Dunkle cycle.

- **Novel conceptual cycle:** In novel conceptual cycle, mixed air is dehumidified and then this dehumidified air is sensibly cooled in a heat exchanger. After sensible cooling it is passed through WSHE.
- **Three mixed-mode cycles:** In this cycle the evaporative coolers which are used as cooling medium are replaced by regenerative/wet-surface heat exchangers.

5. Comparative analysis

5.1. Ventilation cycle

The basic configuration of a ventilation cycle is shown in **Figure 9**. In ventilation cycle, hot and humid process air passes through the rotating desiccant wheel and its dry bulb temperature increases and humidity decreases. The process air is then cooled by passing through a heat recovery wheel. The further cooling of process air is achieved using an evaporative cooler according to the set-values of supply air temperature and humidity. For ventilation cycle, the exhaust air stream from the conditioned space is cooled and humidified close to saturation using an evaporator cooler. The quantity of air coming at point 5 is normally equal to quantity of air entering at point 4. The exhaust air is sensibly heated to precool the process air. Finally, the regeneration air stream is heated and is passed through desiccant wheel for its regeneration, which allows the continuous operation of the dehumidification process. For ideal desiccant wheel the air at the exit of the wheel will be completely dehumidified and specific humidity at point 2 will be zero [14].

$$\omega_{2, ideal} = 0 \quad (1)$$

The heat recovery wheel is basically a counter flow heat exchanger. The desiccant wheel and heat recovery wheel latent effectiveness in term of specific humidity and energy balance for the adiabatic desiccant wheel can be represented as:

$$\varepsilon_{DW} = (\omega_1 - \omega_2) / (\omega_1 - \omega_{2, ideal}) \quad (2)$$

$$(\omega_1 - \omega_2) h_{fg} = (h_1 - h_2) \quad (3)$$

$$\varepsilon_{HRW} = (T_2 - T_3) / (T_2 - T_6) \quad (4)$$

In the evaporative cooler, air undergoes a process of adiabatic dehumidification. On psychrometric chart, this process follows constant wet bulb temperature line.

$$\varepsilon_{EC1} = (T_3 - T_4) / (T_3 - T_{w3}) \quad (5)$$

$$\varepsilon_{EC2} = (T_5 - T_6) / (T_5 - T_{w5}) \quad (6)$$

In case of equal process and regeneration air flow rates, energy balance on the adiabatic heat recovery wheel can be written as:

$$(h_2 - h_3) = (h_7 - h_8) \quad (7)$$

Sensible effectiveness of the desiccant wheel is given by:

$$\varepsilon_{DW,T} = (T_2 - T_1)/(T_8 - T_7) \quad (8)$$

After achieving the temperature and humidity at each state point of the cycle, the cooling capacity, regeneration load and coefficient of performance can be deduced from the following relations.

$$Q_{cool} = (h_5 - h_4) \quad (9)$$

$$Q_{reg} = (h_8 - h_7) \quad (10)$$

$$COP = Q_{cool}/Q_{reg} \quad (11)$$

5.2. Recirculation cycle

The basic configuration of a desiccant cooling system operating on regeneration cycle is shown in **Figure 10**. In recirculation mode all the process remains the same as that of ventilation cycle except the air leaving from the conditioned room is mixed with the process air at point 1 instead of circulating it on the regeneration side. On the regeneration side, fresh ambient air is used. For regeneration cycle the thermal COP of the system is given as:

$$COP = \dot{m}_p(h_1 - h_4)/\dot{m}_r(h_7 - h_8) \quad (12)$$

6. Results and discussion

The conditions of air at different points of the cycle operating on both cycles are obtained using the developed mathematical model in the preceding sections. The effectiveness of both evaporative coolers and heat recovery wheel is considered to be constant for this analysis. The conditions of the supply air are one of the important parameter which plays a major role on performance and amount of latent load removed from the room by the system. The climatic conditions used for this analysis and required temperature and humidity ratio of the supply air is presented in **Table 1**.

The obtained results for yearly average value of COP, required heat, and cooling capacity are presented in **Table 2**. It can be observed that, the system operating on ventilation cycle has higher value of average COP as compared to regeneration cycle. The difference in the performance of both cycles is because of required regeneration heat as illustrated in **Table 2**. The cooling load for both cycles remains almost same because of small difference in conditions of air at points 1 and 5. The difference of regeneration heat is because of temperature difference between point 7 and 8 ($T_8 - T_7$). In this analysis T_8 (regeneration temperature) is set to a constant value of 120°C. The temperature at point 7 has higher value in case of ventilation cycle as compared to recirculation cycle. This larger difference makes the required regeneration heat higher for recirculation cycle as compared to ventilation cycle. Note that, average values of performance parameters are calculated when $T_{ambient} = 35^\circ\text{C}$, regeneration temperature of 120°C, process air flow rate 1.5 kg/s, and both regeneration and process mass flow rates are equal. The detailed results for monthly COP of the system operating on both cycles are presented in **Figures 12 and 13**. The system operating under ventilation and recirculation cycle has a maximum COP of 0.81 and 0.52, respectively for the month of September.

Month	Outdoor air			Room supply air		
	Dry bulb Temperature (°C)	Humidity Ratio (g _v /kg _a)	Wet bulb Temperature (°C)	Dry bulb Temperature (°C)	Humidity Ratio (g _v /kg _a)	Wet bulb Temperature (°C)
April	30.14	13.19	21.10	17.31	9.81	15.19
May	33.21	14.27	22.05	18.74	9.91	16.70
June	39.54	15.71	24.69	18.52	10.11	15.88
July	41.51	20.55	28.97	17.44	10.23	14.10
August	37.28	20.39	27.94	18.32	10.45	15.23
September	37.01	23.52	29.50	18.51	10.12	16.90
October	34.34	15.53	24.47	17.43	9.55	15.77
November	28.71	16.34	23.50	18.54	9.23	15.13
December	23.53	12.94	18.88	18.16	8.88	15.01

Table 1. Climatic data and desired supply conditions.

Parameter	Ventilation Mode	Recirculation Mode
Q _{cool} (kW)	44.40	45.2
Q _{reg} (kW)	99.58	128.21
COP	0.461	0.354
Regeneration temperature (°C)	120	120

Table 2. Average performance parameters for desiccant cooling system operating on ventilation and circulation cycle.

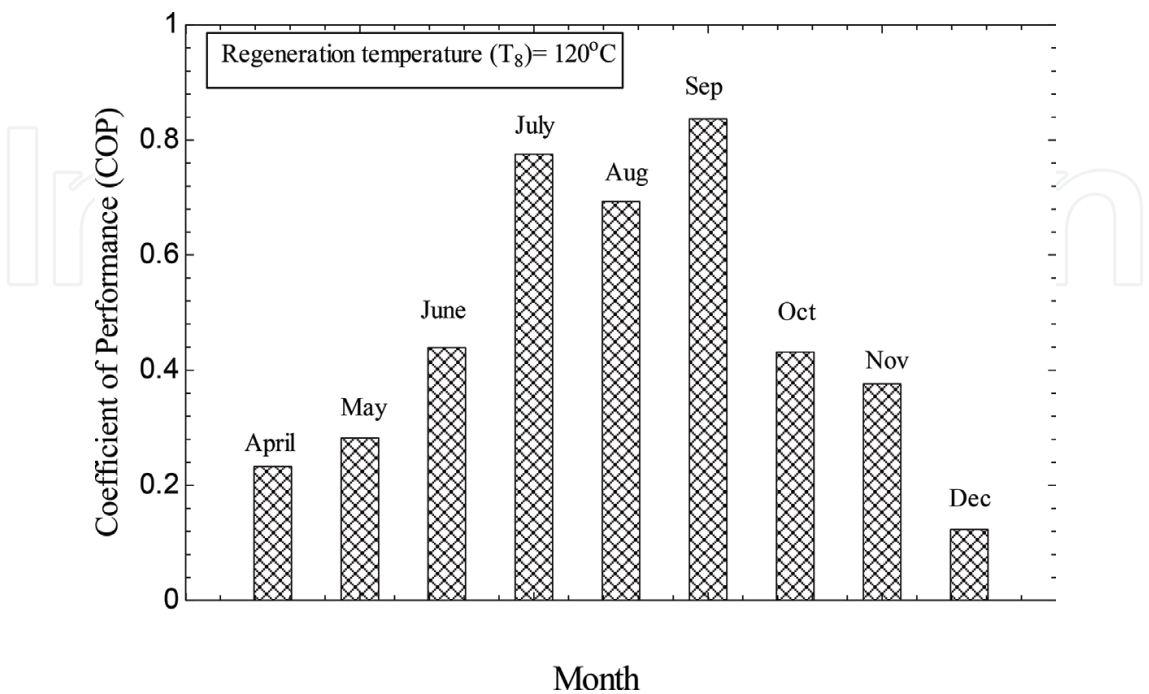


Figure 12. Monthly variations of COP for ventilation cycle.

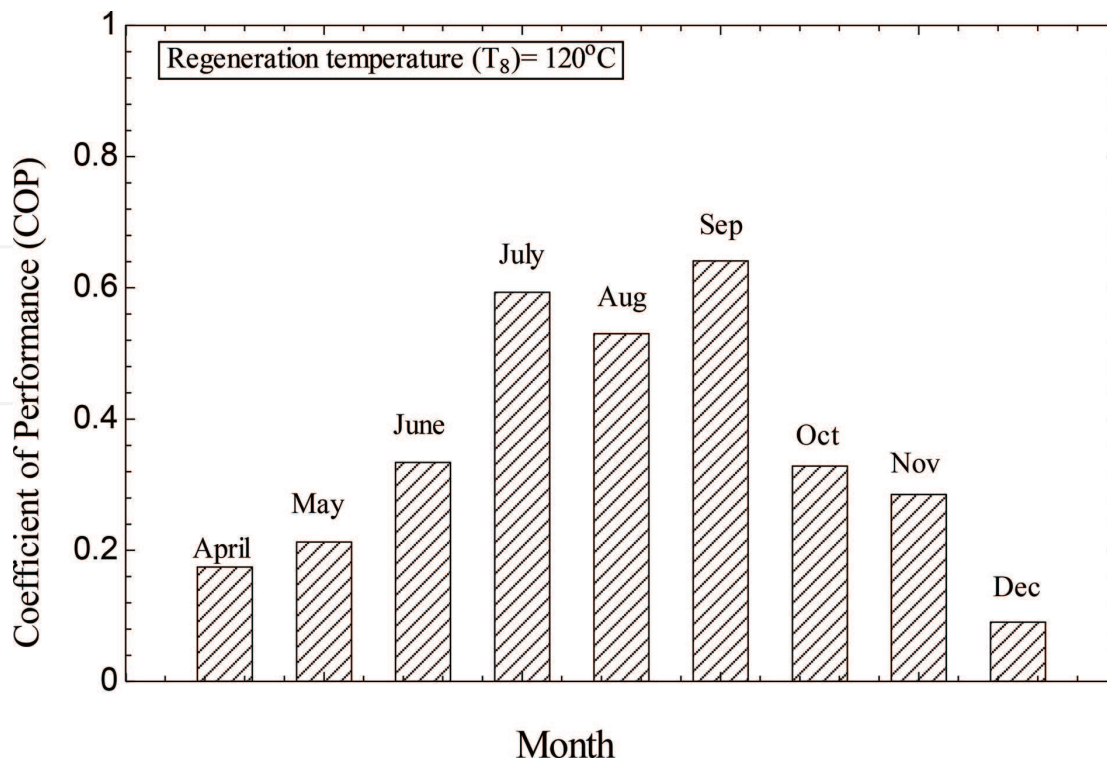


Figure 13. Monthly variations of COP for recirculation cycle.

7. Economic evaluation

In this section, an overview of economic aspects related to desiccant cooling technology has been presented. The economic evaluation of desiccant cooling system has been carried out by different researchers. Abdel-Salam and Simon [15] evaluated a membrane based liquid desiccant cooling system for its enviro-economic aspects. They compared primary energy consumption of four different systems. The obtained results showed that the primary energy consumption and total life cycle cost of desiccant cooling system was lower than conventional system by 19 and 12%, respectively. Addition of energy recovery ventilator improved the difference by 32% for primary energy consumption and 21% for total life cycle cost. Li et al. [16] compared vapor compression cooling system and hybrid of desiccant system for energy and economic evaluation. The results indicated that replacing the conventional system with hybrid system would reduce the size from 28 to 19 kW leading to annual effective energy savings of nearly 6760 kWh. However, the payback period would be 7 years because of the added initial investment costs.

The costs of system accessories will vary depending upon the required flow rates and cooling needs [9]. The sizing charts for fans and pumps are shown in **Figures 14** and **15**, respectively. It can be observed that cost of each accessory depends upon the required output. The small desiccant cooling systems have higher specific costs as compared to large units. A comparative analysis of system specific cost with respect to its size is presented in **Figure 16**. The specific installed system costs are 7300 EUR/kW for small-scale systems and in average 1900 EUR/kW for large-scale systems [17].

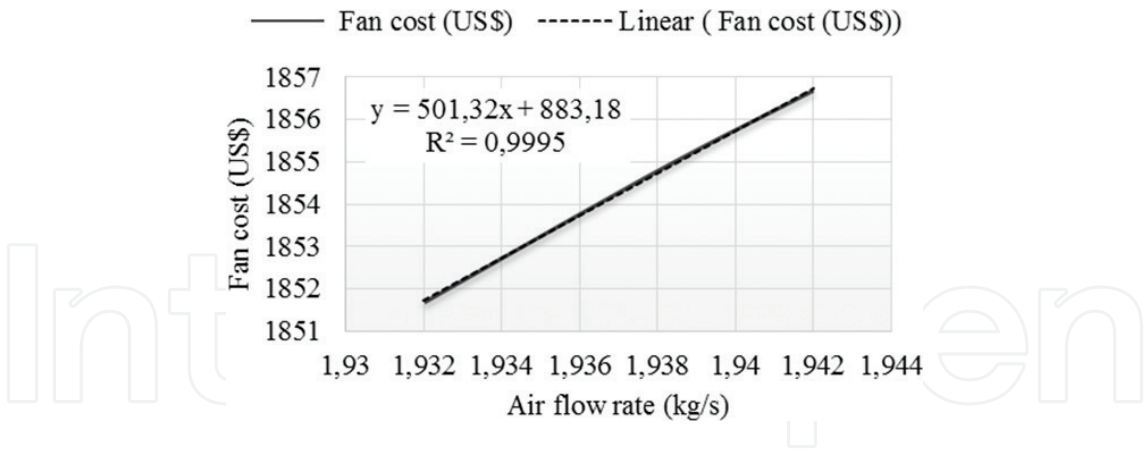


Figure 14. Cost of fan [9].

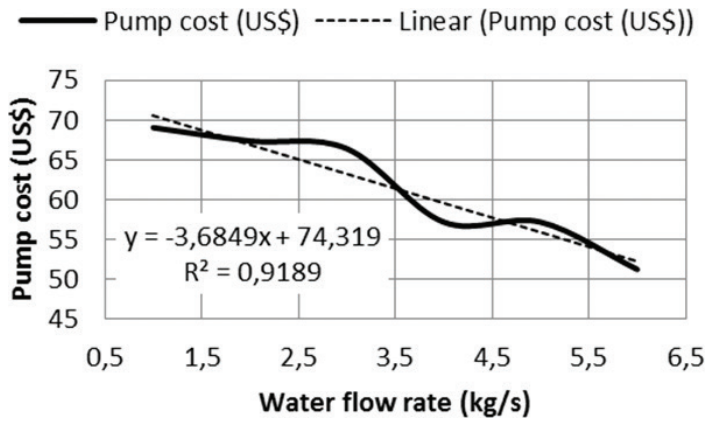


Figure 15. Cost of pump [9].

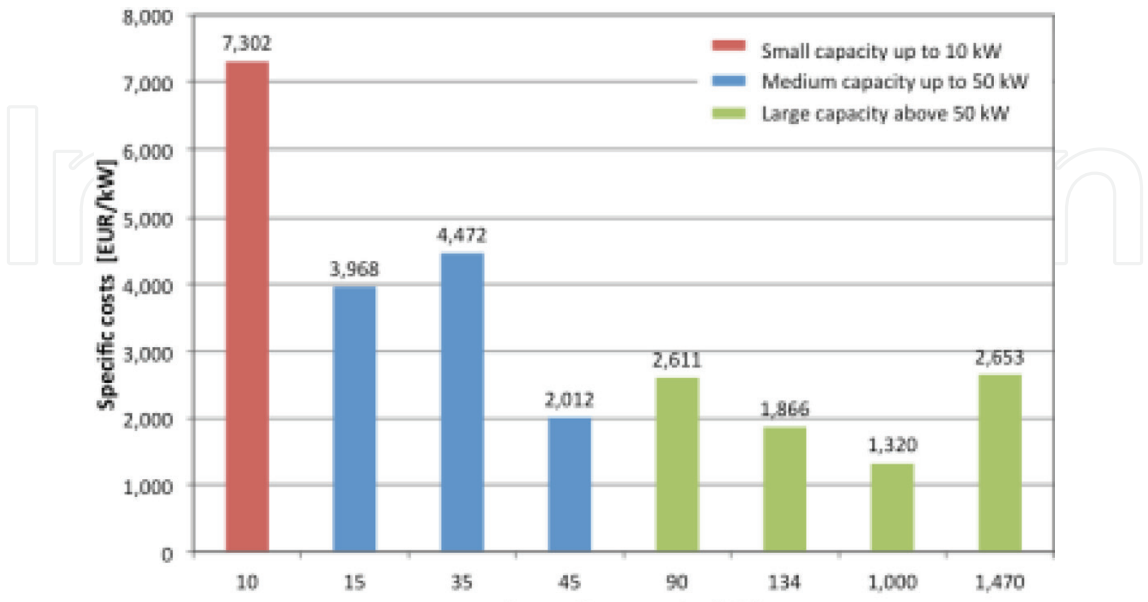


Figure 16. Specific costs of thermal cooling systems. Source: Green Chiller.

8. Recent developments and future needs

The performance and development of desiccant cooling systems strongly depends on the desiccant materials used. The thermo-physical properties of these materials affect the performance of the system significantly. The key parameter for the selection of a desiccant material is that it should have the ability to absorb and hold large amount of water vapor. It should be desorbed easily by providing heat input.

The properties such as density, vapor pressure, etc. of different desiccant materials can be enhanced by mixing two or more materials together. The mixed desiccants are termed as composite desiccants. Many researchers have studied the properties of composite desiccant materials in order to study their effects on dehumidification performance of the system. **Table 3** provides a summary of some experimental studies on desiccant cooling systems and lists the regeneration temperature and desiccant material used [18–24]. The literature review showed that most of the experimental studies were conducted with silica gel at high regeneration temperatures. There is currently limited research conducted with desiccant wheel other than silica gel.

Although, a number of developments have been made in desiccant cooling technology but a number of steps still needs to be addressed in order to make this technology more market accessible. Some of the future research and development needs are:

- Cost-effective, non-corrosive, and nontoxic liquid desiccant materials need to be developed.
- The effectiveness of regenerator needs to be improved using several approaches including multiple-effect boilers and vapor compression distillation. Different alternative energy sources should be utilized for regeneration purpose.
- Surface enhancements or extended surfaces such as fins should be used to modify the design of dehumidifier and regenerator for better heat and mass transfer.

Author	Desiccant material used	Regeneration temperature
Jia et al. [18]	Silica gel	60–120°C
White et al. [19]	Zeolite and polymers	50–80°C
Enteria et al. [20]	Silica gel	60–80°C
Eicker et al. [21]	Lithium chloride, Titanium dioxide, silica gel, silica gel and calcium chloride	45–90°C
Angrisani et al. [22]	Silica gel	60–70°C
Enteria et al. [23]	Silica gel, Titanium dioxide	60–80°C
Wrobel et al. [24]	Lithium Chloride	45–50°C

Table 3. Summary of literature for regeneration temperature and desiccant materials.

- Advanced indirect evaporative coolers should be integrated with liquid dehumidification system to make the system more commercial.
- The system should be developed for longer operation to avoid possible operating problems in industrial applications such as acidifying the desiccant, foaming, etc.

Research and development of liquid desiccant cooling system requires more efforts from experts in the area. Design activities needs to be developed to make this technology accessible to all people in different parts of the worlds.

9. Concluding remarks

The HVAC load can be reduced significantly using renewable energy based desiccant cooling systems due to lower requirement of input power for these systems and effective utilization of alternative resources of energy. These systems prove to be an effective alternative to conventional cooling systems which are energy inefficient and as well as minimize greenhouse gases emissions. In this chapter, a comparative study has been presented among two different configurations of a solar desiccant cooling system operating in the hot and humid climatic condition. The two desiccant cooling cycles namely, ventilation and recirculation are solved theoretically to analyze and compare the system performance. The results showed that COP of the system operating on ventilation mode is higher than the system operating on recirculation mode. Therefore, based on the condition of ambient air, solar desiccant cooling system under the ventilation mode is more suitable than the recirculation mode. This paper also analyzes monthly performance of the system operating under both modes. Furthermore, the analysis of the supply air condition shows that the system is able to provide human thermal comfort in humid climates and it can be an alternative for the conventional air conditioning system. The economic evaluation shows that the larger systems have lower cost as compared to smaller units.

Although progress has been made in the development of this alternative cooling technology but a number of steps still needs to be taken in order to make this technology more market accessible. More research should be conducted on other innovative desiccant cooling systems integration, taking into consideration the associated investment costs. The development in liquid desiccant technology is in progress and it has attaining stability in the market. Furthermore, in order to access this technology in comparison to conventional cooling systems, hidden costs of fossil fuels should be accounted. Understanding the hidden impacts of fossil fuels is critical for evaluating the true cost of conventional power generation systems and has to be communicated to the community.

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Nomenclatures

h	specific enthalpy (kJ/kg)
h_{fg}	specific enthalpy for water (kJ/kg)
\dot{m}	mass flow rate (kg/s)
Q_{cool}	cooling load (kW)
Q_{reg}	regeneration heat (kW)
T	dry bulb temperature (°C)
T_w	wet bulb temperature (°C)

Greek letters

ω	humidity ratio (kg _v /kg _a)
ε	effectiveness

Subscripts

a	air
DW	desiccant wheel
DCS	desiccant cooling system
HRW	heat recovery wheel
EC	evaporative cooler
p	process
r	regeneration
v	vapor
1, 2, 3,....	state points

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