Energy Conversion and Management 256 (2022) 115380

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Review

Separate sensible and latent cooling technologies: A comprehensive review

Omar M. Zaki [a], Ramy H. Mohammed [a,b], Omar Abdelaziz [a,*]

[a] Department of Mechanical Engineering, The American University in Cairo, AUC Avenue, New Cairo 11835, Egypt
[b] Department of Mechanical Power Engineering, Zagazig University, Zagazig 44519, Egypt

A R T I C L E I N F O

Keywords:
Separate sensible and latent cooling
Hybrid cooling
Primary COP
Desiccant
Dehumidification
Challenges

A B S T R A C T

Conventional air conditioning (AC) systems provide simultaneous sensible and latent cooling. This requires air to be cooled below its dew point temperature resulting in low energy efficiency, particularly at low sensible heat ratios where supply air might be reheated. Furthermore, conventional ACs may not be able to simultaneously control the indoor temperature and humidity. These issues have stimulated the research community and industry to pursue advanced cooling technologies like separate sensible and latent cooling (SSLC) technology. This review paper comprehensively discusses the features of different SSLC configurations. It reviews the state-of-the-art of electrically and thermally driven configurations presented over the past two decades using the primary coefficient of performance (COP_p) to compare their performance. This review paper also outlines the challenges and opportunities facing SSLC technologies through indicative cost analysis, typical maintenance required, and future energy mixes effect on COP_p. It is concluded that the vapor compression cycle (VCC) is more suitable for handling the sensible load, while the desiccant wheel (DW) is a good candidate for handling the latent load. However, DW needs more development at the component and system level for the SSLC to compete with conventional AC systems. Moreover, SSLC is still a developing technology that can benefit from additional prototypes evaluation from the energy and economic point of view to accelerate its commercialization. Finally, it was found that the increased penetration of sustainable energy resources would further support the lead of electrically driven cooling technologies based on the VCC.

1. Introduction

The global energy consumption is predicted to increase by 50% in 2050 compared with 2010. This increase is driven by three major sectors: industry, transport, and buildings [1]. Cooling and heating of buildings represent 36% of the energy consumption of the buildings sector [2] indicating a necessity for improving the performance of the cooling and heating devices. In a conventional cooling system, cold and dehumidified air is supplied into the space to remove the sensible and latent loads simultaneously. Fresh air requirements in the space can be met by infiltration or mixing outdoor air with indoor air before processing it [3,4]. However, fresh air increases the total load on the cooling space [3], specifically increasing the latent load in humid locations [4]. To remove the latent load, the process air must be exposed to a surface whose temperature is well below its dew point to induce water vapor condensation and decrease the water content accordingly. This approach has a negative effect on efficiency. Therefore, enhancing the efficiency of cooling and heating systems is critical to mitigate electric consumption, especially in developing countries [5,6].

Reverse Carnot cycle defines the thermodynamic limits of the maximum COP available for a refrigeration cycle, which defines the framework of cooling device efficiency improvement. The Carnot COP can be improved by reducing the heat sink temperature (condenser temperature) and/or increasing the heat source temperature (evaporator temperature), as demonstrated in Fig. 1, thereby creating an opportunity to improve the actual cycle efficiency.

Air-conditioning system design depends greatly on the load's sensible heat ratio, which is the ratio between sensible load and the total (sensible and latent) load. Advanced energy design guides for buildings and modern practices feature a better thermal envelope which reduces the sensible load and minimizes air infiltration. These design guides reduce the total cooling load; but the sensible heat ratio is increased since the internal latent load remains nearly the same.

Conventional systems handle both loads simultaneously using the same device. It would require operating the evaporator at a relatively low temperature below the supply air dew point, which is not required while handling the sensible load. Thus, the low side of the cycle is reduced, resulting in a lower Carnot COP and consequently lower system COP. Other drawbacks of the conventional cooling system are the

* Corresponding author.
E-mail address: Omar_abdelaziz@aucegypt.edu (O. Abdelaziz).

https://doi.org/10.1016/j.enconman.2022.115380
Received 30 November 2021; Received in revised form 19 January 2022; Accepted 11 February 2022
Available online 24 February 2022

Nomenclature

COP	Coefficient of performance
f	Electrical energy conversion factor
$\dot{Q}$	Heat capacity, W
$\dot{W}$	Power, W
Abbreviations	
AB	Absorption
AC	Air conditioning
AD	Adsorption
DEC	Direct evaporative cooling
DOAS	Dedicated outdoor air system
DW	Dehumidification wheel
EC	Evaporative cooling
EW	Enthalpy wheel
HDC	Hybrid desiccant cooling
HVAC	Heating, ventilation, and air-conditioning
HX	Heat exchanger
IEC	Indirect evaporative cooling
LD	Liquid desiccant
MAC	Mobile air conditioning
MD	Membrane dehumidification
PCM	Phase change material
PV	Photovoltaic
PVT	Photovoltaic thermal
R&D	Research and Development
RC	Radiant cooling
RH	Relative humidity
SD	Solid desiccant
SHR	Sensible heat ratio
SSLC	Separate sensible and latent cooling
SW	Sensible wheel
TR	Ton of refrigeration
VCC	Vapor compression cycle
Subscripts	
Elec	Electrical
P	Primary
th	Thermal
c	Cooling

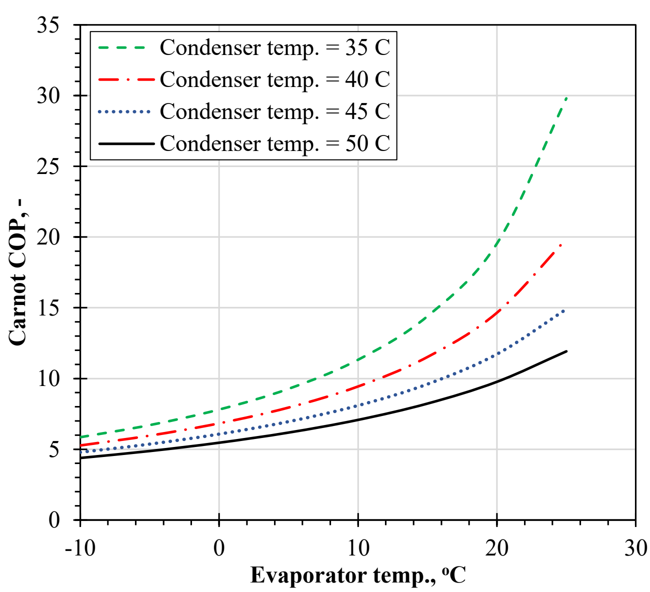

Fig. 1. Carnot COP as a function of evaporator and condenser temperature.

inability to control both humidity and temperature simultaneously, causing relative humidity to be shifted from design value in case of changing sensible heat ratio [7]. Uncontrolled relative humidity might cause serious health issues, especially airborne-transmitted infectious bacteria, and viruses [8-10]. For low sensible heat ratio cases where the latent load is high, reheating might also be required, causing the system efficiency to decrease further.

The separate sensible and latent cooling (SSLC) system was proposed to deal with sensible and latent loads separately, and hence controlling the temperature and relative humidity independently and dynamically. This would be achieved by using a separate cooling device for each load type. Separating loads allows designing more efficient devices to target each load independently. This would allow for operating the low side of the cooling cycle at higher temperature for a sensible cooling device, resulting in a higher Carnot COP limit that would increase the system efficiency [7]. This provides an opportunity to use waste thermal energy or solar thermal energy to operate either the sensible or latent cooling device, reducing or eliminating the electric energy consumption compared with the conventional system that depends mainly on electric power. This would translate to higher electricity saving, making the SSLC system a potential candidate replacing the conventional system.

Fig. 2 compares the energy consumption of conventional and SSLC systems for the same cooling load and sensible heat ratio Fig. 2. At a high SHR of 0.85, The SSLC system showed energy-saving potential by increasing the apparatus dew point from 11.61 °C for the conventional system to 14.45 °C for SSLC with the same supply temperature. Elevating the supply temperature (e.g., to 20 °C) would allow for more energy-saving potential by elevating the apparatus dew point temperature (e.g., to 18 °C); However, the corresponding increase in supply flowrate must be considered. Assuming a 40 °C condenser temperature (i.e., high temperature limit), this translates to 10.9% energy-saving for the same supply temperature used and 24.2% energy-saving for the SSLC system elevated supply temperature (see Fig. 2(a) and (b)).

At a low SHR of 0.6, the SSLC system shows obvious energy-saving potential by increasing the apparatus dew point from 8.94 °C for the conventional system to 14 °C for SSLC. SSLC also shows high energy-saving potential by eliminating the waste of energy caused by the reheating process. Assuming a 40 °C condenser temperature (i.e., high temperature limit), this translates to 78.3% energy-saving for the same supply temperature used (see Fig. 2(c) and (d)) using electric reheat or 35.6% energy-saving using waste energy for reheat process.

Research and development in SSLC technology have increased remarkably in recent years. Experimental and numerical studies have been employed to investigate different SSLC configurations to achieve energy efficiency and thermal comfort in buildings. Energy saving of 14 to 47% could be achieved using the SSLC systems [11]. Several review articles were presented in open literature focusing on limited configurations. For instance, Jani et al. [12] presented a review paper about desiccant-based cooling systems and showed their potential of reducing energy consumption in buildings. Rafique et al. [13] reviewed hybrid evaporative coolers with desiccant systems and discussed their suitability in hot and humid climatic conditions in which desiccants can handle the latent load efficiently. To the best of our knowledge, there is no recent review paper that covers different SSLC configurations available in literature. The review paper presents an overview of the present status of SSLC technology. First, a classification of cooling technologies utilized in SSLC systems with points of strength and weakness of each

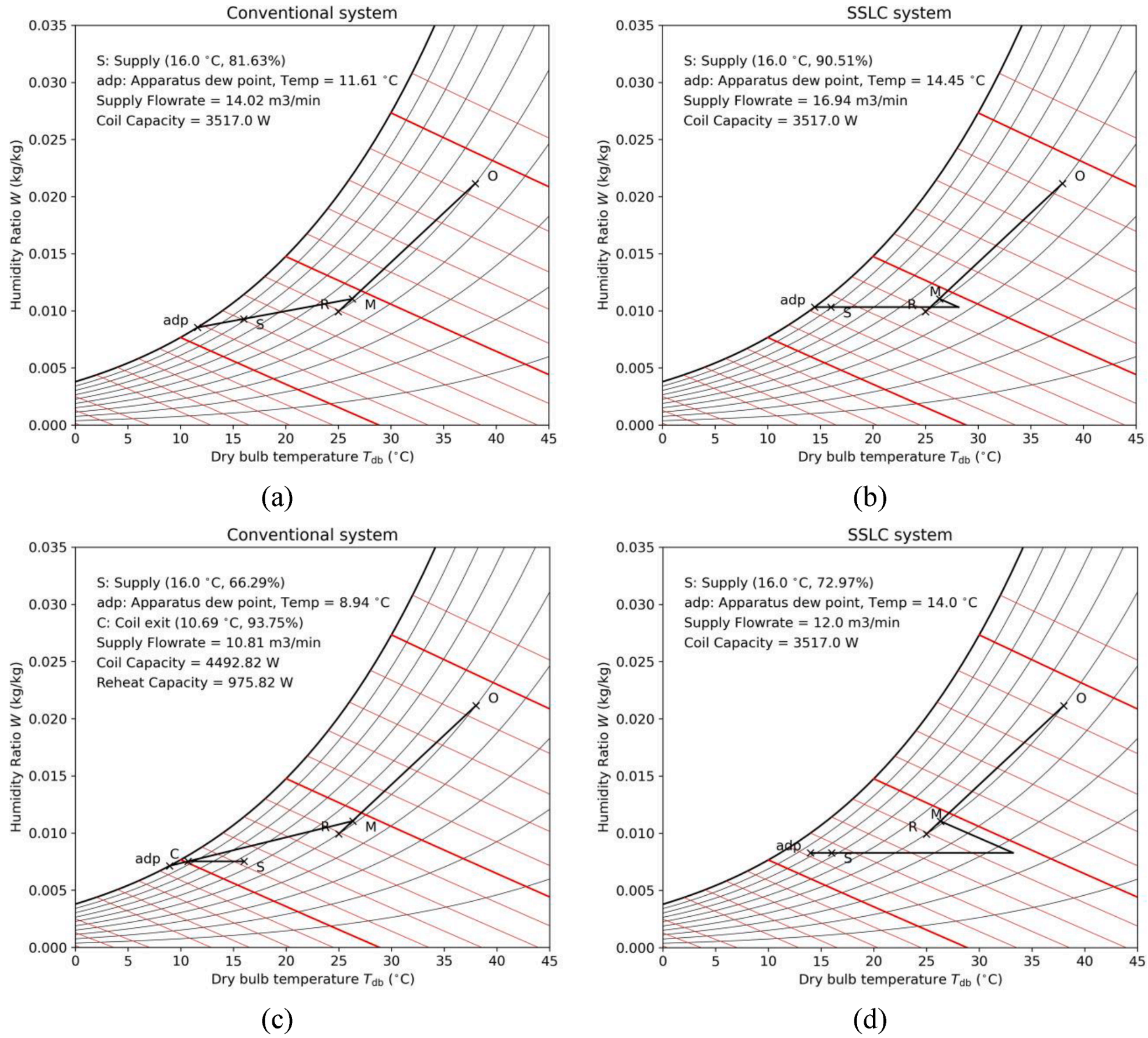

Fig. 2. Psychrometric chart for conventional and SSLC system. (a) Conventional system at SHR = 0.85, (b) SSLC system at SHR = 0.85, (c) Conventional system at SHR = 0.6, (d) SSLC system at SHR = 0.6, O: outdoor point (38 °C, 50%), R: indoor point (25 °C, 50%), M: coil inlet point (26,32 °C, 51.36%).

technology is provided. A comprehensive literature review is then introduced for different configurations presented in open literature employing SSLC technology. The following section provides a comparison based on primary COP between different configurations and summarizes their operating conditions. In the last section, opportunities and challenges for research and development related to SSLC technology are identified with a discussion on indicative cost and typical maintenenace schedule for the different systems. This section also provides a glimpse on the impact of future energy mix on the performance of the different system configurations. We believe that this review provides the scientific community with an overview of state-of-the-art SSLC technology that promises energy efficiency and identifies research gaps to further the impact of SSLC.

2. Classification of separate sensible and latent cooling systems

Cooling devices can target all the cooling load, sensible cooling load only or latent cooling load only. A classification of cooling devices based on the targeted cooling load is used here. These devices could be driven by thermal or electrical energy. This section describes the working principle, features, advantages, and disadvantages of each device.

2.1. Total cooling devices

Total cooling devices decrease both air dry bulb temperature and water content. This can be achieved by cooling air below its dew point which causes water vapor in the air to condense on the surface of the cooling device. The most common technologies used in such systems are vapor compression cycle (VCC), absorption cooling (AB) and adsorption cooling (AD).

The VCC is the dominant, well-established, and mature technology [14]. The basic cycle is shown in Fig. 3a, and consists of an evaporator, condenser, expansion device, and compressor driven by electricity. VCCs have can operate reliably over a wide range of operating conditions and is not restricted by the ambient humidity. The electrical COP (ratio of cooling capacity to electric energy consumption) of VCC is relatively higher, but it is an energy-intensive technology [15].

Thermally driven sensible load handling technologies have been developed and called not-in-kind (or non-VCC) technologies. AB cooling systems are an alternative to the VCC. The main difference between the

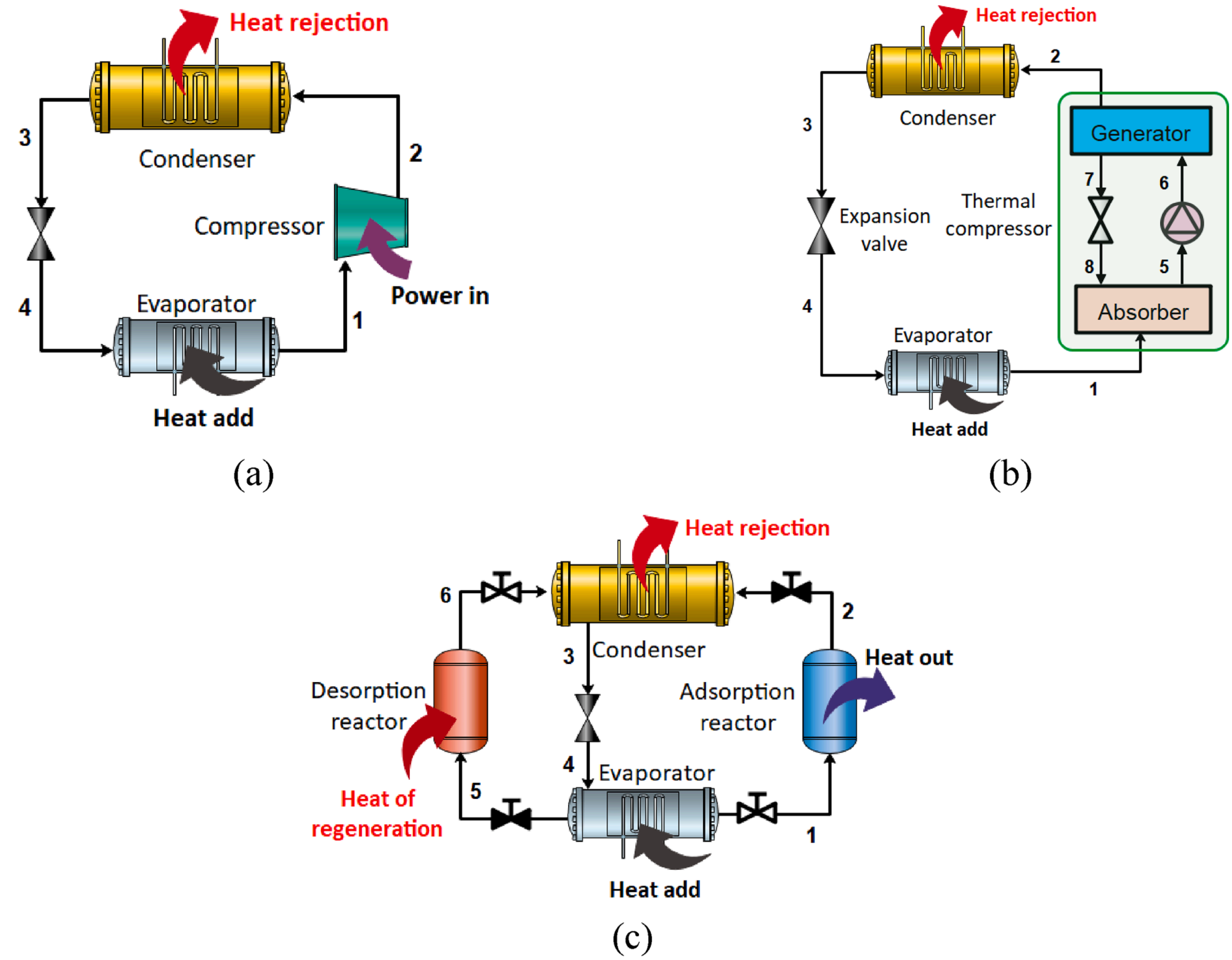

Fig. 3. Total load handling devices: (a) vapor compression cycle (b) absorption cycle, (c) adsorption cycle.

two cycles is replacing the compressor with four components that act as a thermal compressor: generator, absorber, expansion device, and liquid pump, as shown in Fig. 3b. Typically, pumping a liquid requires significantly less energy than compressing a gas, hence compression power is replaced with much lower pumping power and absorber heat rejection fan/pump; However, significant thermal energy is required to desorb/regenerate the fluid in the generator [16,17]. Therefore, solar energy or low-grade thermal energy is usually employed to drive the AB cycle. Water-LiBr and ammonia-water are usually used in the AB cycle as working fluid pairs (refrigerant/absorbent). The thermal COP of absorption systems (ratio of cooling capacity to thermal energy consumption) is less than 1.0 for most simple cycles and slightly higher than 1.0 for more complex designs [18].

The AD cycle is similar to the absorption system, except the liquid absorbing fluid is replaced by solid adsorbent (SD) (desiccant). Thus, the electric compressor of VCC is replaced by an adsorption bed, as drawn in Fig. 3c. The cycle has two adsorption beds to alternate between the adsorption and desorption processes and guarantee continuous operation and cooling effect [19]. During the adsorption process, the bed should be cooled to facilitate vapor diffusion into the solid adsorbent. This process is slower than vapor diffusion into liquid absorbers, resulting in lower thermal COP compared with AB cycles. The thermal COP of such systems is usually less than 1.0 [20]. AB and AD cycles could be powered by solar energy or low-grade waste heat. Table 1 summarizes the main features of total cooling technologies.

2.2. *Sensible cooling technologies*

Sensible cooling of air happens when the dry bulb temperature of the air decreases without affecting its water content. This is done by removing heat from the air through a surface whose temperature is higher than air dew point temperature. The driving force of such process is the temperature difference between air and the cold surface, making sensible cooling achievable. Several sensible cooling technologies have been proposed and studied in literature. VCC, AB, and AD cycles can be designed to provide sensible cooling only by increasing the evaporating temperature, thereby increasing the cycles' efficiency. However, the most common technologies published in literature are evaporative cooling (EC) and radiant cooling (RC). Fig. 3 presents a schematic diagram for each cycle.

Indirect evaporative cooling (IEC) device is another technology that could handle the sensible load. Typically, it has dry and wet channels, as presented in Fig. 4a [21]. Primary air enters the dry channel while secondary air moves into the wet channel. The secondary flow exchanges heat and mass with water, allowing its temperature to decrease. The cool and humid secondary air exchanges heat with primary air, causing a decrease in its temperature. As a result, the primary air exits dry channels at low temperature without changing its moisture content. IEC can achieve a very high electrical COP exceeding 15 [22]. The main drawback of IEC is that it is suitable for dry climates where water scarcity might be a problem with the high water-consumption rate. The Maisotsenko Cycle, (M−cycle) [23], is an advanced dew-point IEC technology that utilizes part of the primary air stream as the secondary

Table 1
Summary of the advantages and disadvantages of total cooling devices.

Technology	Main Energy Source	Advantages	Disadvantages
VCC	Electrical	• Very mature in design • High electrical COP. • Simple. • Variety in working fluids. • Low maintenance. • Low initial cost.	• Most working fluids have a harmful impact on the environment. • Uses Electricity, a high-grade energy source. • The compressor which is the heart of the system is a moving part with the possibility of wear.
AB cycle	Thermal with electrical auxiliary	• Can utilize low-grade thermal energy sources. • Pump is the only moving part that is easy to replace or repair. • The working fluid is environmentally friendly. • Can operate with design thermal COP at part loads by changing generator operating temperature.	• Complex design. • High initial cost. • Bulky design. • Low thermal COP around one. • Needs continuous maintenance for systems that use lithium bromide due to its corrosive nature.
AD cycle	Thermal with electrical auxiliary	• Can utilize low grade thermal energy sources. • Handling solids is easier than fluids. • Working medium is environmentally friendly and not corrosive. • Continuous operation with little maintenance.	• Complex design. • High initial cost. • Thermal COP less than one.

air stream in a counter-flow heat exchanger arrangement; a sequential decrease in primary air temperature using multi-stages might also increase the effectiveness of the M−cycle to achieve near-dew-point cooling effect. A modified M−cycle is proposed where primary air passes through dry channel, and secondary air passes through dry channel then wet channel to help increase the system effectiveness.

RC is achieved by cooling a surface of the space (usually the ceiling) where sensible heat is removed from the air through radiation and natural convection as shown in Fig. 4b. Such systems are operated with cold water having a temperature higher than the dew point of the space air to prevent condensation of water vapor on the cold surface. Due to the small heat transfer coefficient and driving difference in temperature between space air and cold surface, the time response of such systems is slower than other technologies utilizing forced convection and higher driving temperature difference. Furthermore, the radiant cooling panel temperature is limited by the indoor dew point to avoid condensation issues. This results in limited cooling capacity that may compromise the indoor comfort conditions for large cooling load applications.

There are other types of cooling devices that can produce a cooling effect, such as compressor-driven metal hydride heat pump that depends on the exothermic and endothermic cyclic effect of pumping hydrogen between two metal-hydride reservoirs [24], thermoelectric refrigeration, which depends on the Peltier-Seebeck effect [25], thermotunneling which depends on electrons carrying heat across a gap and not allowed to return due to a voltage difference [26], and magnetic refrigeration which depends on magnetocaloric effect [27]. These systems are still under development. [28,29]

Table 2 summarizes the main features of sensible cooling technologies.

Table 2
Summary of the advantages and disadvantages of sensible cooling devices.

Technology	Main Energy Source	Advantages	Disadvantages
EC	Electrical auxiliary	• The only power consumption is for the fans. • Very good performance in dry locations. • Simple design. • Low initial cost. • Can achieve very high values of electrical COP that are not possible with other technologies.	• High water consumption. • Not suitable for humid locations.
RC	Electrical or thermal	• Driven by cold water, so any cooling technology can be used. • More stable air dry-bulb temperatures over time.	• Slow time response. • Might not be sufficient in high cooling loads.
Other types	Mostly electrical	• Good potential for future development.	• Low performance compared with other technologies. • Inability to utilize in large capacity applications.

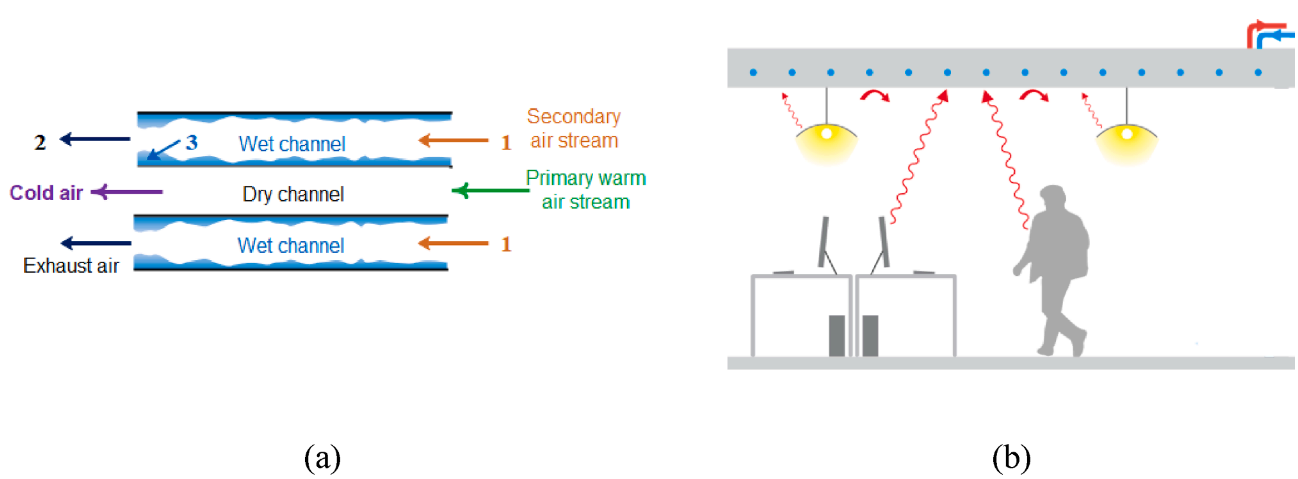

Fig. 4. Sensible load handling devices: (a) indirect evaporative cooling (b) Radiant Cooling.

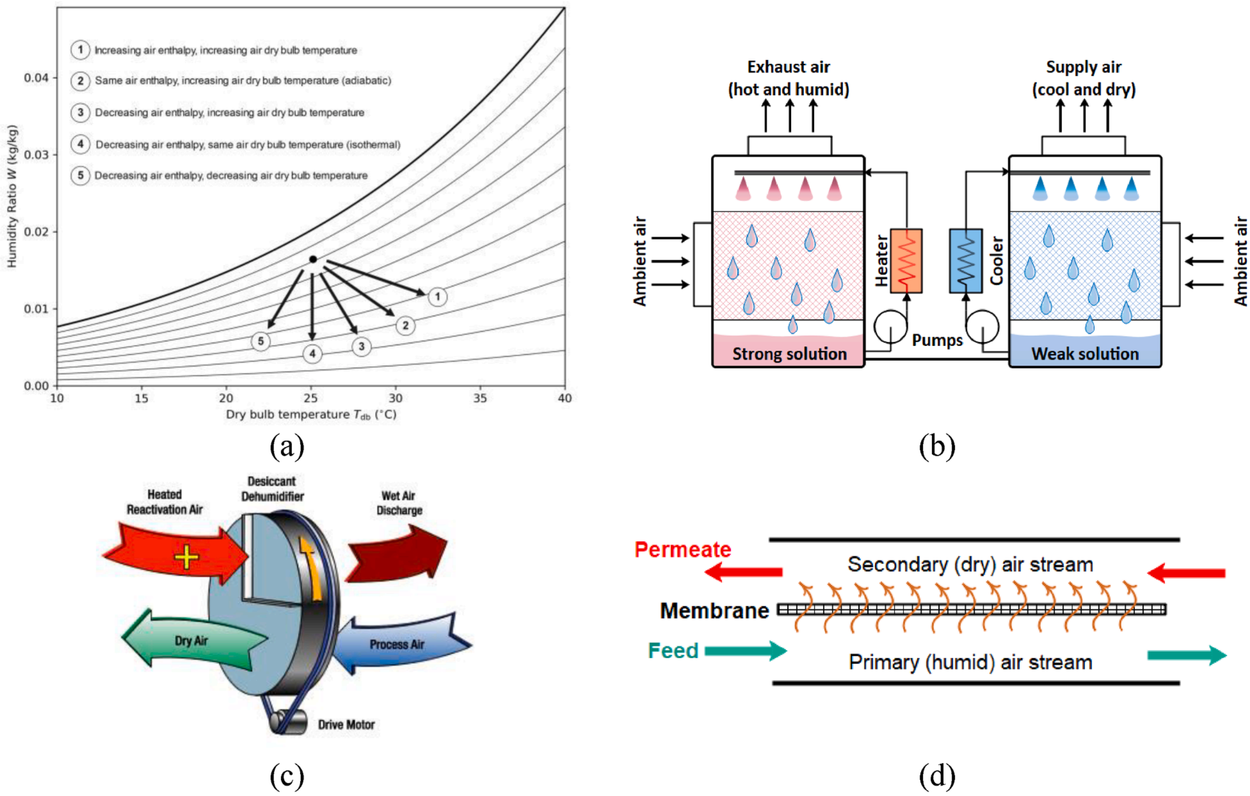

Fig. 5. Latent load technologies (a) psychrometric representations for different scenarios, (b) LD cycle, (c) DW device, and (d) membrane dehumidification.

2.3. Latent cooling technologies

Latent cooling of air happens when the water content of the air decreases. This is done by condensing water vapor on a surface whose temperature is lower than the air dew point temperature or absorbing water vapor through a concentration gradient. VCC, desiccant systems, and membrane dehumidification are widely used to handle the latent load in the SSLC system (see Fig. 5). VCC would be able to handle the latent load if the evaporating temperature is less than the air dew point (which how latent load is handled in conventional systems), but this can cause overcooling and the necessity for reheating the supply air again; This reheating process causes the energy efficiency of the system to decrease significantly.

Desiccant materials (either liquid or solid) are used to absorb/adsorb water vapor from moist air. This process is driven by the gradient in water vapor pressure. Depending on the desiccant material temperature, the dehumidification process can increase, decrease, or have no effect on air enthalpy and dry bulb temperature, as shown in Fig. 5a. The liquid desiccant (LD) dehumidification system has two chambers, as presented in Fig. 5b [30]. The liquid desiccant systems have several advantages: they cause low air pressure-drop which would require less fan power, they can also be regenerated with a low-grade thermal heat source having low regeneration temperature, and the regenerated liquid desiccant does not have to go through a cooling process as it can be stored until heat is dissipated [31]. However, using LD systems may cause problems: liquid desiccants are corrosive, carry-over might raise health concerns and corrode air ducts, and aqueous salts desiccants might crystallize which affect the system reliability [32]. Solid desiccant (SD) cycles usually utilize the rotary desiccant wheel (DW), as illustrated in Fig. 5c [33]. They can be incorporated in different cycles such as the ventilation cycle proposed by Pennington [34], recirculation cycle [33], Dunkle cycle [35] and wet surface heat exchanger cycle [36].

Jain et al. [37] investigated the four cycles at different ambient conditions of several cities in India. It was found that the wet surface heat exchanger cycle gives the best performance. In general, using solid desiccant is less complicated than using liquid desiccant as handling solid desiccant material is easier with fewer numbers of equipment required and no possibility for leakage. The possibility of carry-over is minimal, unlike liquid desiccants, making the system less susceptible to corrosion.

Table 3
Summary of the advantages and disadvantages of latent load handling devices.

Technology	Energy Source	Advantages	Disadvantages
LD systems	Thermal	• Can utilize low-grade thermal energy sources. • Pump is the only moving part that is easy to replace or repair. • Storage of liquid desiccant allows for continuous operation even during maintenance and power shortage. • Low air pressure-drop.	• Health issue due to the carry-over of liquid desiccant. • Liquid desiccants are corrosive.
SD systems	Thermal	• Simple design. • Handling solids is easier. • Have been covered thoroughly in literature.	• Not suitable for removing large latent loads. • Bulky systems.
MD	Electrical and/or thermal	• Driven only by a vacuum pump, a compressor or LD. • Excellent performance with high permeability membranes. • Good potential for future development.	• New technology which is still in research.

Membranes are also used in dehumidification purposes because they are selective media that allow the migration of selected species (permeates) using partial pressure (i.e., concentration) gradient, as

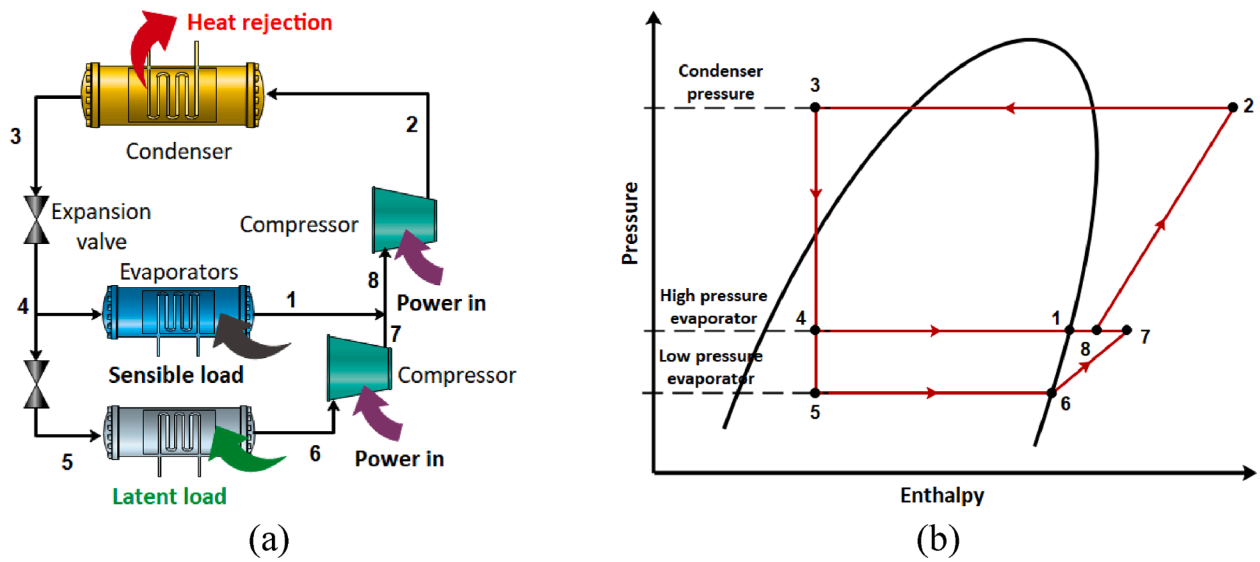

Fig. 6. Schematic for (a) typical dual evaporator VCC and (b) its representation on P-h diagram.

illustrated in Fig. 5d. This process can be achieved by either imposing a pressure gradient between the two sides of the membrane (vacuum membrane) or using a liquid desiccant material (membrane contactor) to force water–vapor migration. Two membrane types can achieve this: dense membranes and porous membranes. Membranes can be produced in flat sheet or hollow fiber configurations [38]. The vacuum membrane and membrane energy recovery ventilator are extensively used in HVAC applications. Membrane energy recovery ventilator transfers both sensible and latent energy. Membranes can have a very high water/air permeability ratio of up to 10,000 [39], giving good dehumidification performance. Table 3 gives an overview of the advantages and disadvantages of each technology used to handle the latent load in HVAC applications.

3. Separate sensible and latent cooling configurations

The sensible and latent cooling technologies discussed previously could be combined to handle the two loads separately. So, either the VCC or not-in-kind technology could be used to handle the sensible heat, while either VCC, desiccant system or membrane dehumidification handles the latent load. The following sub-sections demonstrate different configurations based on the technology that handles the sensible heat.

3.1. Separate sensible and latent cooling based on vapor compression cycle

3.1.1. Modified vapor compression systems

VCC is a mature technology that can handle the sensible and latent load separately by using two evaporating temperatures, as shown in Fig. 6a, instead of one evaporator. This approach is simple and easy to apply and allows to control the indoor temperature and humidity independently. The low-temperature evaporator handles the latent heat, while the high-pressure evaporator deals with the sensible heat. Such arrangement already exists in dual evaporator refrigerators that controls the refrigerator and the freezer temperatures independently and are already commercially available. This arrangement results in energy saving by reducing the compressor work due to lower pressure ratio of refrigerant passing through the sensible load evaporator, as illustrated in Fig. 6b. This approach also reduces the heat rejection in condenser, and hence achieves higher electrical COP. In this direction, Ling et al. [40] conducted a theoretical study on the SSLC system where they estimated energy savings for the SSLC system of 30% compared with the traditional system. They also proposed a new method for air distribution for a single row evaporator that deals with the large volume flow rate of air required with the SSLC system. The new method indicated a 30% reduction in fan power compared with the traditional method. Abdelaziz [41] analyzed 4 different SSLC systems configurations, including a 2-stage VCC system. The primary COP analysis showed that the SSLC technology using VCC only is better than the conventional system at all design conditions. It was reported that the VCC is highly affected by the efficiency of the compressor and slightly by the sensible heat ratio. Liu et al. [42] developed a twin rotary compressor with two independent cylinders. Compared with the traditional twin rotary compressor, the two cylinders of the SSLC compressor used independent suction structures which can control two different evaporating temperatures independently with the same exhaust chamber. The two cylinders may have different intake pressure but the same discharge pressure. They utilized the compressor in a household air conditioning system. The electrical COP of the residential air conditioning system using the SSLC system was 6.55% higher than that of the system using the conventional compressor, and the dehumidification quantity increased by 10.59% [43]. However, the reported electrical COP values of the proposed configuration and the conventional configuration is high compared to relevant studies. Liu et al. [44] did an experimental and theoretical study for VCC having two evaporators working in series, and a mixture of R32/R236fa was employed as a refrigerant. At 7 °C and 17 °C evaporators temperatures, the experimental electrical COP of the system was 3.97 with an exergy efficiency of 31%. The electrical COP increased to 4.14 when the mass fraction of R32 was 60% [45]. Yang et al. [46] used the dual evaporator approach along with a fresh air handling unit for total and sensible energy recovery. The first evaporator was installed in the conditioned space and the other was used inside the fresh air handling unit. They reported an energy saving of about 48.87% compared with the conventional system.

The two-evaporator approach can be utilized by producing chilled water at two different temperatures handling sensible and latent load separately. Chen et al. [47] demonstrated the applicability of using two cooling sources to control the indoor temperature and humidity independently. In comparison with VCC, the proposed system enhanced the electrical COP by 3.1% to 17.5% based on moisture ratio changes. It was concluded that the system is more efficient in a humid climate with high moisture content. Liu et al. [48] used a dual chilling system using R407C instead of the conventional single chilling system and studied energy and exergy efficiency. They found that the proposed system has a 25% increase in both electrical COP and exergy efficiency. The low-

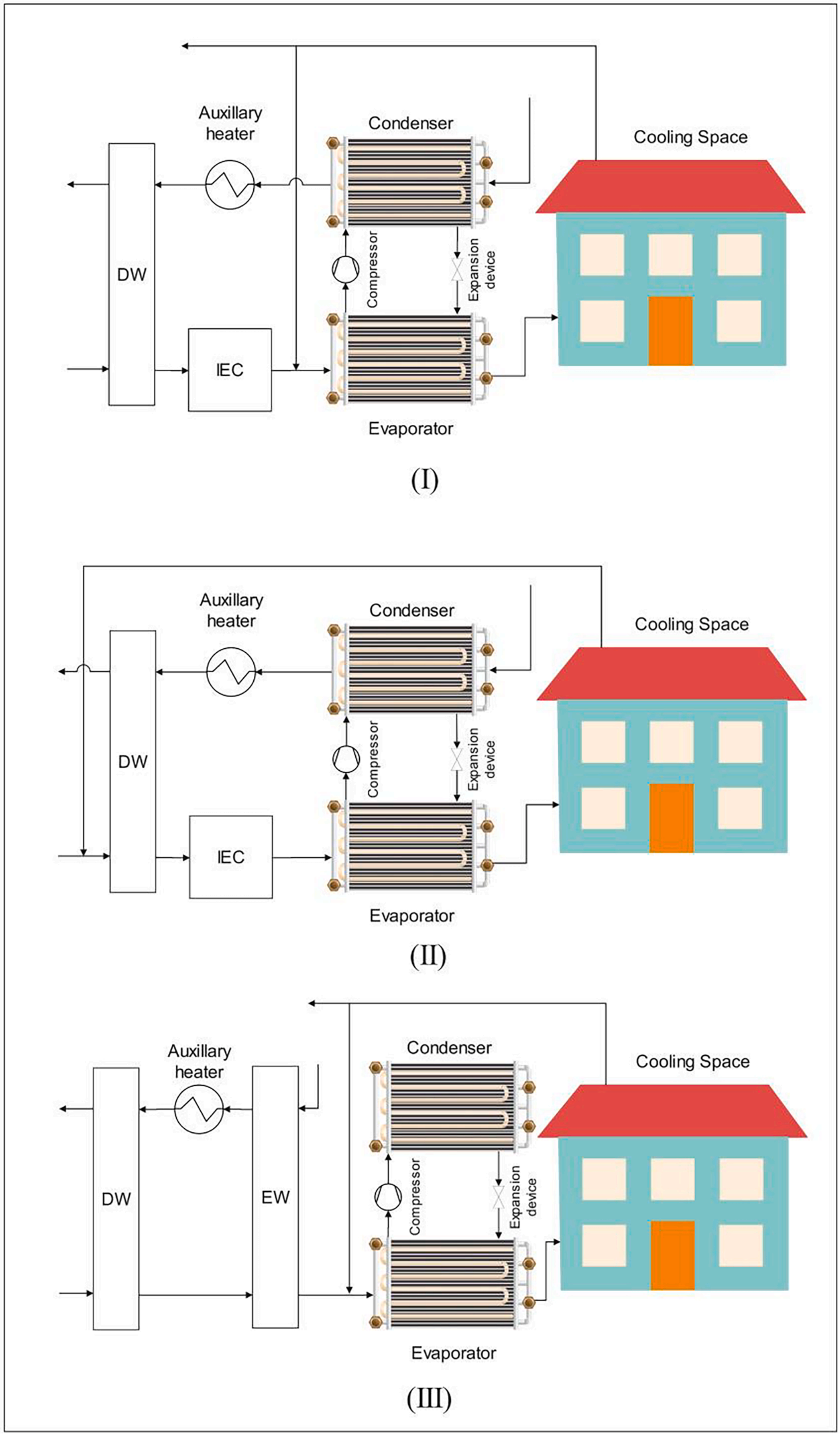

Fig. 7. Configurations proposed by Burns et al. [55] (I) ventilation /condenser cycle (II) recirculation condenser cycle (III) heat exchanger cycle.

temperature chilling water had the major effect on the electrical COP rather than the high-temperature chilling water.

As the sensible load can be handled using temperature difference, radiation can be used to handle the sensible load. Han and Zhang [49] used the sensible load evaporator to supply cold water to radiant panels to handle most of the sensible load and the latent load evaporator supplying cold dry air to handle the latent load and part of the sensible load. They concluded that the units with SSLC configuration achieved a cooling energy saving of 47.8% compared with the conventional air conditioning system that could control both humidity and temperature.

Other methods to mimic the working principle of the SSLC systems exist. However, they cannot be described as SSLC systems with two devices handling each load separately. Zhang et al. [50] achieved separate temperature and humidity control by adjusting the chilled water flow rate and temperature. The proposed system achieved a power saving of 30–50% compared with the conventional VCC. Ma and Horton [51] proposed and experimentally tested a single VCC switching between low evaporating temperature for the combined sensible and latent load and high evaporating temperature for sensible load only. They achieved an energy saving of 6.9% to 11.5% compared with the conventional system.

3.1.2. Hybrid vapor compression and adsorption systems

Sorption (solid adsorption and liquid absorption) technology has been widely used in literature to handle the latent load of buildings [52]. It is mostly used due to its simple design. It can deliver air at lower temperatures than conventional cycle with a marginal penalty on electrical COP [53]. The dehumidification wheel (DW), which contains solid desiccant, is a common example of the adsorption technology for dehumidification. It is usually combined with VCC for SSLC applications. Such integration is usually called a hybrid desiccant cooling system [54]. During the first part of the rotation of DW, the solid desiccant adsorbs moisture from process air. During the second part, regeneration hot air is used to desorb moisture from the desiccant to facilitate continuous working of the device. Sometimes, enthalpy wheel (EW) is used to recover some of the sensible and latent energy from the exhaust air to increase the system overall efficiency; This can be done using a heat exchanger coupled with absorption, adsorption, or membrane technology to transfer total enthalpy (sensible and latent) between the supply and exhaust air steams (hence the name). Sensible wheel (SW) can be used for the same purpose, recovering only the sensible energy though heat-exchange between supply and exhaust air streams. The performance of this hybrid VCC-DW system is usually evaluated using the thermal and electrical COP. The thermal COP (COP_{th}) is calculated based on the thermal energy used to drive the desiccant sub-system, and the electrical COP (COP_{elec}) is the COP of the VCC. In this regard, Burns et al. [55] studied the three different configurations shown in Fig. 7. The same components were arranged in different ways to save energy and meet different load demands. Their study concluded that ventilation-condenser configuration (arrangement I) performed superiorly during the hot-dry and hot-humid climates with a high latent load. However, the conventional system performed well in the hot-humid climate with a low latent load and a high sensible heat factor of 0.75. Operating at low regeneration temperatures gave an advantage to recirculation-condenser configuration (arrangement II) in all climates.

Jia et al. [56] tested a hybrid VCC-DW at 30 °C and 55% RH ambient condition where the VCC had 6-kW cooling capacity. The system used an electric heater for regeneration. The SSLC resulted in 37.5% energy savings compared with the conventional system. Liu et al. [57] proposed and numerically evaluated a dedicated outdoor air system (DOAS) that consists of hybrid VCC-DW. The system could keep the indoor condition steady when the outdoor conditions changed by controlling the regeneration temperature. The electrical COP was estimated to be 3.044 when the outdoor conditions were 36 °C and 13 g/kg (34.7% RH). Hürdoan et al. [58] designed and experimentally tested hybrid VCC-DW with energy recovery wheel, aiming to improve indoor air quality and save the indoor air quality energy. The rotary wheel was coated with silica gel to remove the moisture content. The regeneration heat was found to be the main contributor to energy consumption. The average daily electrical COP was 1.35 due to the use of electric heaters for DW regeneration. These electrical heaters constituted about 62% of the total energy consumed by their system. However, the electrical COP value was similar to previously reported ones in literature for this configuration [59].

Ling et al. [60] experimentally studied CO_2 and R410A hybrid VCC-DW systems under the AHRI [61] standard rating conditions (35 °C, 44% RH). The electrical COP of the VCC increased by 7% compared with the conventional system for both working fluids. Utilizing a desuperheater in the VCC assisted in providing the necessary regeneration energy while reducing the condenser pressure and consequently the compressor work. The electrical COP improved by 36% and 61% compared with conventional system using R410A and CO_2, respectively.

Later, Ling et al. [62] proposed 7 SSLC arrangements employing DW and VCC operating with R410A or CO_2. In the baseline SSLC system (option 1), VCC provided sensible cooling, and its heat rejection (heat of condensation) was used for the desiccant regeneration process resulting in an electrical COP of 2.84 and 4.1 using CO_2 and R410A, respectively. In option 2, the condenser was divided into two parts to decrease the VCC condensing temperature below the regeneration temperature of the DW and hence reduce the compressor's energy consumption resulting in an electrical COP of 4.6 using CO_2 or R410A. They considered evaporative cooling for the air-cooled condenser in option 3 to provide further condensing temperature reduction resulting in an electrical COP of 5.39 and 4.99 using CO_2 and R410A, respectively. In option 4, the condenser was divided into 3 different sections to improve the heat rejection resulting in an electrical COP of 6.32 and 5.22 using CO_2 and R410A, respectively. In option 5, an EW was added to the system to precondition ventilation air before passing through the DW resulting in an electrical COP of 9.07 and 8.61 using CO_2 and R410A, respectively. In option 6, a SW was used in the system with total fresh air supply resulting in an electrical COP of 5.4 and 8.61 using CO_2 and R410A, respectively. In option 7, the SW from option 6 was replaced with EW resulting in an electrical COP of 10.19 and 10.09 using CO_2 and R410A, respectively. It was concluded that CO_2 performed better than R410A with evaporative cooling. Option 3 with CO_2 showed better performance than option 2 because the inlet temperature to the gas cooler was decreased. They also found that the SW was not beneficial for dedicated outdoor air systems unlike EW, as the SW reduced the rejected heat from the VCC which would be used for the regeneration of DW. EW did the same but also reduced the regeneration energy requirement for the DW.

Khosravi et al. [63] introduced energy, entropy, and exergy analyses of a hybrid VCC-DW compared with conventional VCC-based systems. The exergy-economic analysis proposed by Bejan et al. [64] was applied to conventional VCC and SSLC systems installed in hot-humid climates. It was concluded that the SSLC is the most economical system. It was also found that the SSLC system of solid desiccant coupled with VCC provides 19.78% energy savings with cost reduction for cold process air by 14.5% compared with the conventional system. Sheng et al. [65] utilized a hybrid VCC-DW with silica-gel as desiccant to handle the sensible and latent heat independently. Return air was mixed with fresh air before entering the system. The heat of condensation was used as a regeneration heat to save the cost of a component and energy. The electrical COP changed from about 1.6 to 2.08 as the outdoor humidity ratio varied from 10 to 20 g/kg. Jiang et al. [66] conducted experimental testing for a hybrid VCC-DW to handle the latent and sensible heat where VCC had a variable refrigerant flowrate, respectively. Experimental measurements revealed that the electrical COP of the system varies from 4 to 4.7 when tested during July and August in Shanghai, China. Alabdulkarem et al. [67] designed and tested a prototype of 3.5-kW hybrid VCC-DW for SSLC. The theoretical results showed an improvement in the electrical COP by 30% compared with the baseline unit while the experimental results showed lower electrical

COP than the baseline due to design issues.

Jani et al. [68] used TRNSYS to simulate a room with 1.8 kW cooling load using a hybrid VCC-DW system under hot and humid climates. The system was sensitive to regeneration temperature and outdoor humidity ratio. The electrical COP was recorded using a regeneration temperature of 100 °C. The electrical COP of the system reached 5.5 at ambient conditions of 30 °C and 16 g/kg (59.6% RH). The same group [69] experimentally studied the performance of a hybrid VCC-DW with a heat recovery wheel in 3 × 3 × 3 m room in Roorkee, India, from March to mid-October. The sensible and latent loads were 1.37 and 0.39 kW, respectively. The DW was able to reduce the humidity ratio by 61.7%. The system was found to be sensitive to outdoor conditions and air flowrate. The electrical COP was about 2.0 at an ambient temperature of 32 °C. Lee et al. [70] studied a hybrid VCC-DW SSLC system for mobile air conditioning (MAC). Applying the solid desiccant to the MAC system provided 26.3% reduction in energy consumption.

Nie et al. [71] performed a theoretical and experimental analysis of a hybrid VCC-DW using a silica gel DW. In their system, the process air exits were used as fresh outdoor air. Two condensers were used; one was used for the regeneration process and the other removed surplus heat of condensation. The electrical COP of VCC reached 3.47 at outdoor conditions of 20.63 °C and 14.01 g/kg (91.4% RH). The electrical COP decreased to 2.75 at outdoor conditions of 38.28 °C and 17.04 g/kg (39.9% RH).

Another approach is coating the VCC heat exchangers with the desiccant material. Tu et al. [72] coated the evaporator and condenser of the VCC with an adsorbent material. A control system was used to switch between the evaporator and condenser for continuous operation. The desiccant material handled the latent heat under a nearly isothermal process. Therefore, the electrical COP of the system reached more than 7.0 without scarifying the compactness of the system. Jani et al. [73] studied a similar combination using TRNSYS simulations with different configurations during the summer. Experimental tests were also performed to study the effect of operating parameters on the performance of the system. The study was performed on a 49-m^3 room. The sensible and latent loads of the room were 1.37 and 0.39 kW, respectively, giving a sensible heat ratio of 0.78. indoor conditions were maintained at 25 °C dry bulb temperature and 55% RH. The system could reduce the humidity ratio of the process air significantly from 14 to 6 g/kg using the DW. Decreasing regeneration from 70 °C to 50 °C caused the electrical COP to increase from 1.82 to 2.51 at ambient temperature of 31 °C.

Choi and Choi [74] combined DW with VCC in series in a hybrid VCC-DW where the evaporator was placed in space to provide sensible cooling. This work aimed to find the optimized matching between the two cycles to achieve the highest energy saving. At the optimized configuration, the electrical COP of the system was estimated as 6.9, with a reduction in energy consumption by 20–30% compared with the hybrid evaporative cooler with DW cycle.

Solar energy was used for the regeneration process of the sorption unit. In this regard, Ma et al. [75] presented simulation results for a hybrid VCC-DW with 2 silica gel adsorption units. The system was powered by 150 m^2 solar collector in Shanghai, China. The condensation heat of the heat pump was employed for the regeneration process. The electrical COP of the studied HVAC system was higher than that of conventional VCC by 44.5%. Beccali et al. [76] did an energy and economic investigation for three solar-driven configurations: DW, DW with EW, and hybrid VCC-DW. The simulation analysis showed that the hybrid VCC-DW system is preferable from the economic point of view because it consumed less energy and required a smaller solar collector. Fong et al. [77] conducted year-round dynamic simulation using TRNSYS software for 6 different arrangements using VCC, EC, and DW. Three arrangements used 100% fresh air and the other three used 100% return air. PV, PVT, and evacuated tube solar collectors were used in 4 cases to save energy and reduce CO_2 emissions. All investigated cases were feasible with about 35.2% saving in energy consumption compared with conventional VCC. It was concluded that using an evacuated tube solar collector to provide hot water for the regeneration process is more economical than using PV or PVT panels.

Fong et al. [78] compared the performance of a solar hybrid VCC-DW system with a conventional centralized air-conditioning system for commercial premises with high latent cooling load in subtropical Hong Kong. They investigated two cases for a Chinese restaurant and wet market. The SSLC system used solar energy for the regeneration of desiccant material. They found that solar energy could be sufficient for the regeneration of the SSLC system. The system achieved annual primary energy savings of 49.5% and 13.3% for the Chinese restaurant and the wet market, respectively. La et al. [79] performed experimental and theoretical analysis for solar-driven two-stage hybrid VCC-DW. They used a 90 m^2 solar collector for the DW regeneration. The average thermal and electrical COP reached 1.24 and 11.48, respectively, under extreme humid conditions. Al-Alili et al. [80] modeled and investigated a hybrid VCC-DW system powered by a PVT collector for Abu Dhabi climate conditions. Their parametric study concluded that the total COP of the proposed system is higher than that of conventional air conditioners powered by solar PV panels by a factor of 2.0.

Hands et al. [81] used two-rotor DW in a hybrid VCC-DW to handle 12,000 m^3/hr air. It was concluded that the DW powered by solar energy could handle 35% of the total space cooling load. Angrisani et al. [82] modeled the dynamic performance of a solar-assisted silica gel DW in a hybrid VCC-DW using TRNSYS software. Techno-economic analysis was performed for different solar collectors with several inclination angles installed in Benevento and Milano in Italy. The payback period for the extra capital cost of SSLC configuration over the conventional system was estimated to be 8 and 6 years for Milano and Benevento, respectively, due to the higher energy requirement in the former city.

Luo et al. [83] studied an SSLC system using a solar-assisted hybrid VCC-DW. Heat rejection from VCC condenser was utilized in the regeneration process. Experimental studies were performed in the hot-humid climate of Taichung, Taiwan, from the spring to fall seasons. The SSLC system reduced power consumption by about 10% by utilizing a solar-assisted hot-water system for regeneration compared with the baseline SSLC system. As the ambient humidity ratio increased, the performance of SSLC system improved. The optimal electrical COP of the SSLC system was achieved at an ambient temperature of 26–27 °C for the baseline SSLC system and 27–30 °C for the solar-assisted SSLC.

Liu et al. [84] proposed and modeled a solar hybrid VCC-DW with silica-gel desiccant. The solar collector provided thermal energy for the regeneration process and the PV panels to power the VCC. Their analysis showed that increasing the regeneration temperature and ventilation ratio caused cooling capacity and dehumidification capacity to increase. A ventilation ratio of 90% produced the highest dehumidification capacity of 12 g/kg. The size of the system increased as the outdoor humidity ratio and condensation temperature increased. The thermal COP estimated based on the heat of regeneration was recorded to be about 2.75 using a regeneration temperature of 55 °C, while the electrical COP was 6.25.

3.1.3. Hybrid vapor compression and liquid dehumidification systems

The liquid desiccant (LD) dehumidification (i.e., absorption) cycle has been widely used to handle the latent heat. Mohammad et al. [85] reviewed many SSLC based on the LD cycles and concluded that the system's performance depends on the selection of liquid desiccant. It was also recommended to use solar energy for the regeneration process. Studak and Peterson [86] evaluated different liquid desiccants to identify the most promising for HVAC applications. It was concluded that $CaCl_2$ is promising due to its high heat transfer and low cost. However, its corrosive nature might raise concerns in design. Kinsara et al. [87] showed that integration between heat pump and $CaCl_2$ LD dehumidification cycle could reduce the energy consumption by more than 30% compared with conventional VCC. Dai et al. [88] designed a hybrid LD-VCC consisting of a VCC, liquid desiccant dehumidification, and EC. The total COP was about 23 % higher than the VCC alone when the

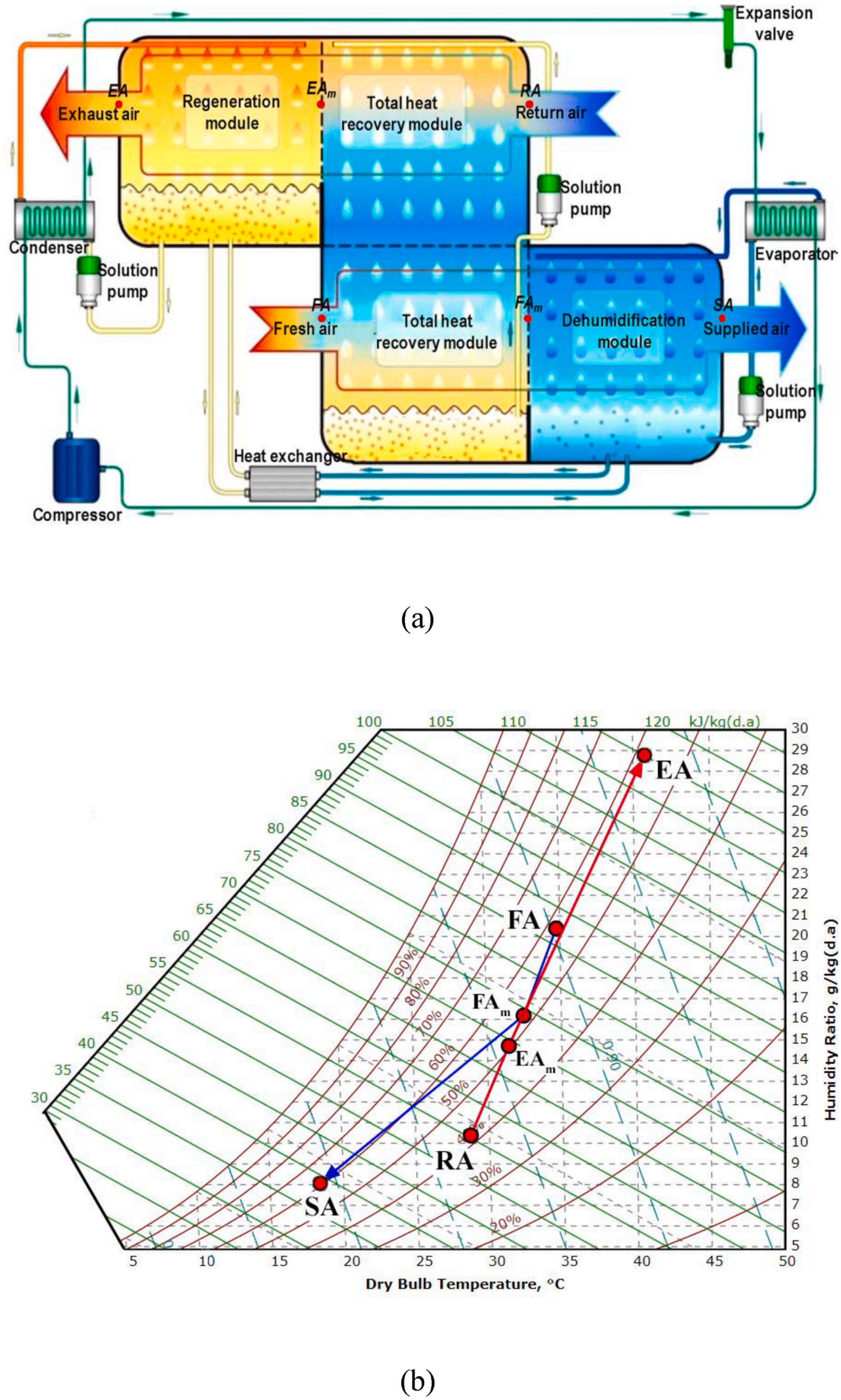

Fig. 8. Hybrid heat pump and LD: (a) schematic of the proposed system; and (b) processes representation in the psychrometric chart [92]

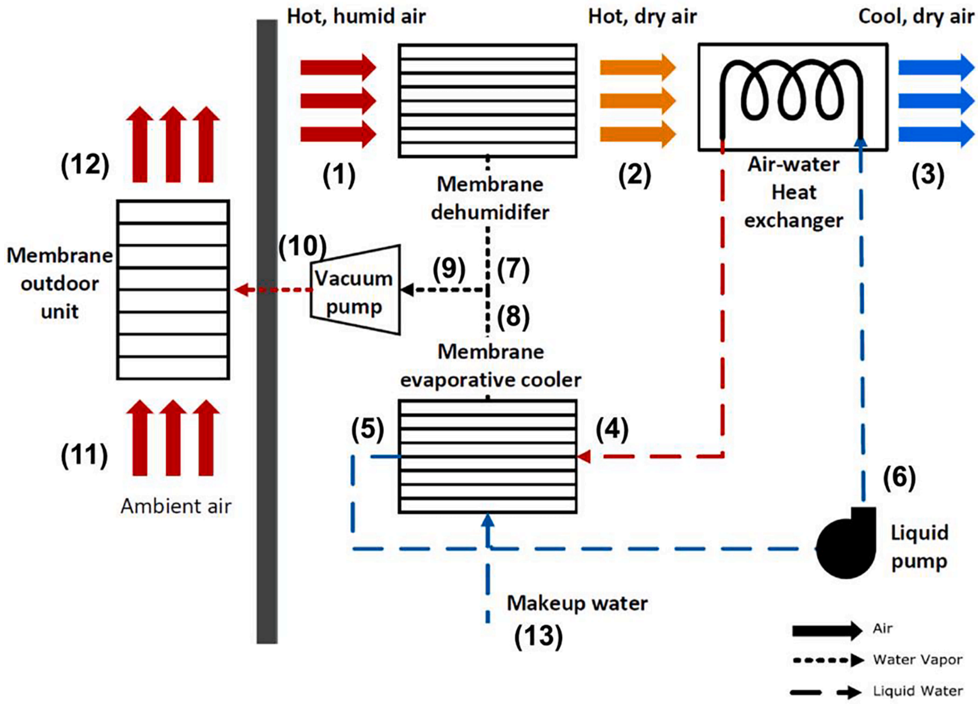

Fig. 9. Integrated heat pump and membrane system [109]

dehumidification was considered. Li et al. [89] built and tested a hybrid LD-VCC with LiBr as desiccant for a hospital in China. Experimental tests showed that the electrical COP was 5.3 in the Summer and 4.3 in the Winter at 24 °C indoor air dry-bulb temperature.

Khalil [90] built a hybrid LD-VCC with LiCl as desiccant and tested it under north Egypt climate conditions (20–30 °C and 35–45% RH). The electrical COP was measured to be 3.8, which was 68% higher than conventional VCC with electric reheat. The system produced a total cooling capacity of 1.75 TR, and the system's payback period was 10 months. Yamaguchi et al. [91] proposed hybrid LD-VCC with LiCl as desiccant in which the regenerator and absorber were integrated into the condenser and evaporator, respectively. Performance of the system was evaluated experimentally and numerically based on heat and mass transfer balance across each component in the system. The isentropic efficiency of the compressor was calculated to be 63%, and the effectiveness of the solution heat exchanger was 0.5, which negatively affected the electrical COP. Increasing the compressor efficiency led to significant improvement in the electrical COP. The supply air cooled from 30 to 22.2 °C, while the total electrical COP was 2.71 and the electrical COP of VCC was 3.82.

Zhao et al. [92] proposed a hybrid LD-VCC for HVAC application, as shown in Fig. 8. Field test was conducted for an office room in Shenzhen, China, and the measurements demonstrated a significant energy-saving in comparison with the traditional HVAC system. The electrical COP was estimated to be 4.0. Bergero and Chiari [93,94] established a hybrid LD-VCC with LiCl as desiccant. Simulation results showed that 60% energy saving could be achieved at a higher latent load. Zhang et al. [95,96] used the same configuration under heating and cooling modes. For the heating mode, the electrical COP was 30–40% higher than that of heat pump coupled with an electric heater. Niu et al. [97] studied a hybrid LD-VCC with a double-condenser heat pump and LiCl as desiccant. They focused on capacity matching of the components used in the SSLC system during dynamic operating conditions and found that controlling solution flowrate, compressor speed and air flowrate in condenser simultaneously is mandatory to achieve capacity matching. The electrical COP was estimated using a mathematical model as 1.38, which is relatively low compared with other studies using the same configuration.

Xie et al. [98] built a mathematical model to evaluate the performance of hybrid LD-VCC. The regenerator and dehumidifier were counter-flow packed towers. The heat of condensation of the heat pump was used for the regeneration process. The total electrical COP of the system was 9.7 and could be further improved when a two-stage heat pump was used. Liu et al. [99] performed numerical analysis for the heat and mass transfer of a hybrid LD-VCC. Evaporator and condenser load were used to facilitate the absorption and regeneration processes, respectively. The electrical COP reached 6.68 when the solution heat exchanger effectiveness was 1.0 and decreased linearly as it reduced. Guan et al. [100] optimized the flow type (parallel flow, cross flow, and counter flow) of the generator and humidifier of a hybrid LD-VCC to handle sensible and latent load independently. The counter flow configuration showed the highest electrical COP of 7.4, compared with 6.8 and 7.2 for parallel and crossflow arrangements, respectively. The higher performance of the counter flow was due to the better heat and mass transfer in the regenerator and dehumidifier. He et al. [101] evaluated the performance of a solar-driven hybrid LD-VCC with LiBr as desiccant under the climatic conditions of Zhengzhou, China. The proposed system was investigated for cooling and heating mode. The electrical COP of the system was estimated to be 7.08, while the energy consumption was 26.7% less than the conventional VCC.

Mansuriya et al. [102] experimentally tested a hybrid LD-VCC with a 5-kW lab-scale VCC. Evaluating the system's performance at ambient conditions of 37 °C and 60% RH indicated 27.54% improvement in the electrical COP compared with standalone VCC, and a payback period of 4 years. The same group did a thermo-economic analysis for their proposed system [103]. Compared with traditional VCC, the hybrid LD-VCC achieved 68.4% increase in electrical COP and 1.54 year payback period at the optimized conditions. Guan et al. [104] presented a field measurement for a hybrid LD-VCC system installed in a factory located in Xiamen, China. The average electrical COP over the year was 3.6 and resulted in annual electricity saving of 23.3%. Lee and Jeong [105] proposed and laboratory tested a hybrid LD-VCC with LiCl as desiccant. Measurements indicated that the system could handle the loads in The Summer and Winter in Korea. In the cooling mode, the cooling capacity

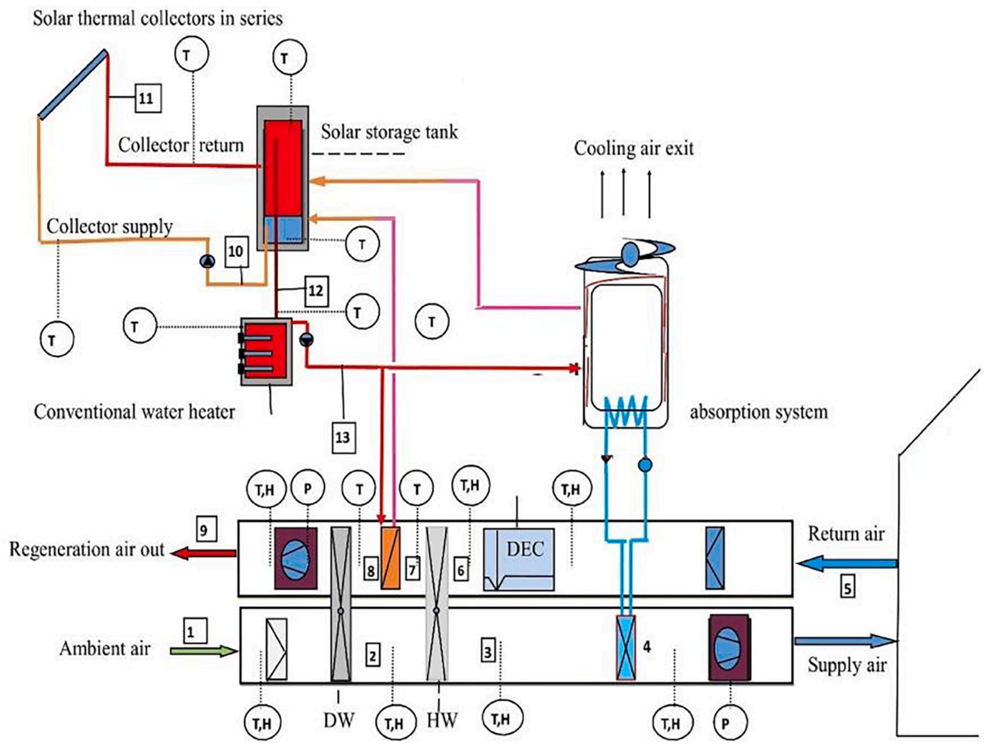

Fig. 10. A hybrid absorption chiller and DW powered by solar energy [113]. Note: HW represents a sensible wheel.

was 7.45 kW, and the total COP of the system was recorded to be 2.26 while in the heating mode, the heating capacity was 5.075 kW, and the total COP was 2.51, which met the minimum requirement of energy performance as recommended in ASHRAE 90.1 [106].

Song et al. [107] performed a parametric study for a solar-regenerated hybrid LD-VCC with dual VCC. Optimization analysis showed that the optimal generator and evaporator temperature are 70 °C and 18 °C, respectively, to achieve the lowest energy consumption at the lowest solar intensity. The thermal COP of the absorption subsystem was 0.747, while the electrical COP of VCC was 3.01.

3.1.4. Hybrid vapor compression and membrane dehumidification systems

Membranes are used for dehumidification purposes in SSLC systems [38]. Gurubalan et al. [108] conducted experiments on an SSLC system having a cooling coil and membrane dehumidifier. Effect of flow arrangement and operating conditions were investigated. The membrane was used to separate between process air and desiccant while cooling water was used to cool the desiccant from the other side. The optimal operation of the dehumidifier was achieved when the cooling water flow was in parallel to air and in counter flow to the desiccant. Bukshaisha and Fronk [109] simulated a membrane heat pump with a cooling capacity of 3 TR in different cities in the US (see Fig. 9). The electrical COP of the proposed system ranged from 4.7 to 5.9. The electrical COP was found to be more sensitive to outdoor wet-bulb temperature than to dry-bulb temperature. The study concluded that the membrane system is suitable and more efficient than VCC in many areas in the US. Compared with VCC, the system could save energy by 25% in Phoenix. However, the membrane fouling was a main concern. Cheon et al. [110] simulated a cooling system that comprised a cooling coil and vacuum membrane dehumidification (VMD). The dehumidification electrical COP (dehumidification cooling capacity to electrical energy consumption ratio) was 1.34 compared to 0.71 for the conventional system that has cooling and heating coils, coupled with enthalpy heat exchanger and 2.7 for the same conventional system with additional active desiccant wheel. Regardless of the low dehumidification electrical COP of the proposed system, it had the potential for energy saving, especially at a low sensible heat ratio. It is important to note that this system relies on the use of vacuum pump which is typically inefficient and not accurately modeled. This would render the modelling results inaccurate.

3.2. Separate sensible and latent cooling based non-vapor compression cycles

3.2.1. SSLC based on sorption technologies

Sorption systems like adsorption and absorption cycles have been used to meet the sensible cooling load in SSLC systems. Miyazaki et al. [111] performed a theoretical analysis for a silica gel 3-bed adsorption cycle having two evaporators at different temperatures handling sensible and latent load separately without a description of a fully integrated system. The system's thermal COP was 1.7 times higher than the conventional 2-bed adsorption cycle with one evaporator with value of 0.65 at nominal conditions. Su and Zhang [112] proposed SSLC that consisted of absorption (AB) refrigeration cycle and LiCl LD. The heat of condensation of the AB cycle was utilized for the regeneration process of LD system. The evaporator of AB handled the sensible load, allowing it to work at a high temperature and hence achieve higher performance. The theoretical analysis indicated that the system could have primary energy efficiency of 0.697 at an evaporator and condenser temperature of 18 and 46 °C, respectively. This value was 34.97% higher than that of a standalone AB cycle. Habib et al. [113] combined AB cycle with DW to handle 10.94 kW sensible load and 4.44 latent load separately. The absorption cycle was used to deliver chilled water for a radiant cooling system to handle the sensible load, as shown in Fig. 10. A flat plate solar collector was used to drive the system. Simulation results from TRNSYS indicated that the proposed system could have a thermal COP of 1.52 with a solar fraction of 56.2%. The standalone absorption cycle had a thermal COP of 0.52.

3.2.2. SSLC based on evaporative cooler

Over the years, several configurations of EC systems have been proposed and investigated [114,115]. Among different arrangements,

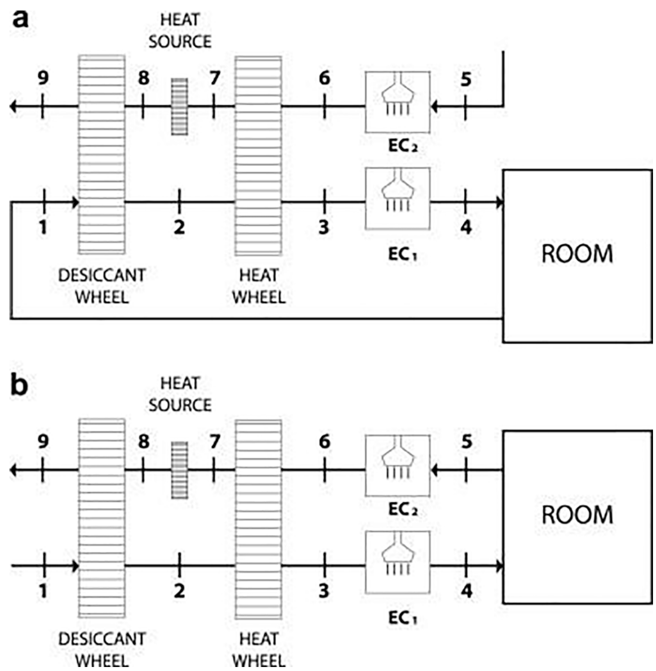

Fig. 11. Schematic of (a) recirculation and (b) Pennington cycle studied by Sphaier and Nobrega [121]

the Pennington cooling cycle [116], ventilation cycle [114], recirculation cooling cycle [114], simplified advanced solid desiccant cooling cycle [114], direct–indirect evaporative cooling cycle [115], and Dunkle cooling cycle [115] have been widely studied.

Yong et al. [117] experimentally tested an IEC and VCC with liquid LiCl desiccant (LD) dehumidification rotor under Hong Kong (high humid climate). Results revealed the significant effect of the regeneration temperature and air flow rate on the system's performance. It was found that the system could provide the required cooling loads with maximum total COP of 0.5 and electrical COP of 3.0. The optimal total COP was recorded using 100 °C regeneration temperature. The system maintained higher total COP at higher ambient temperature owing to the presence of VCC. The system was found to be cost-effective and energy-saving at different operating modes. Chen et al. [118] built an experimental setup of DEC and $CaCl_2$ absorption cycle and tested the system at different operating conditions. The results proved the potential of this system in handling the sensible and latent loads. Under steady-state conditions, the thermal and electrical COP of the system were 0.70 and 2.62, respectively.

Chung and Lee [119] proposed two SSLC configurations and studied the effect and contribution of design parameters on their performance numerically. The two systems consisted of DEC, regenerative EC, heat wheel, and DW. The main difference between the configurations was how the heat wheel operated; for system A, the heat wheel exchanged sensible heat between the supply and return air while between outdoor and exhaust air in system B. Among several parameters, the regeneration temperature was the dominant parameter that contributed by 31.9% and 23.9% in the thermal COP based on an analysis of variance (ANOVA) for system A and B, respectively. The optimization study concluded that system A provides the maximum thermal COP of 1.286. Caliskan et al. [120] removed the DEC from system A proposed in [119] and performed exergy analysis. The system was built and tested in the summer in the Republic of Korea at 35 °C temperature and 39.75% relative humidity. The experimental measurements were used to validate the mathematical model. The electrical COP, thermal COP, electrically driven exergy COP, and thermally driven exergy COP were 6.708, 0.769, 0.463, and 0.198, respectively.

Sphaier and Nóbrega [121] performed a parametric study for the Pennington and recirculation cycle shown in Fig. 11. The results showed that the ventilation cycle could achieve a thermal COP of more than 1.0 at 100% effectiveness of the heat wheel. This COP was reduced by a factor of 2 or more at 80% effectiveness. Worek et al. [122] coupled the M−cycle with DW. Their results showed the potential of this integration to replace VCC. Pandelidis et al. [123] coupled a crossflow M−cycle with silica gel DW to handle the sensible and latent heat independently. Their mathematical model was based on ε-NTU method and was used to investigate the applicability of the proposed system compared with conventional cooling cycle. The regeneration temperature was assumed to be about 55–60 °C, which can be provided by solar panels under ambient conditions of central Europe. It was found that the supply air temperature monotonically increases as the ambient humidity ratio increases, inlet flow rate increases, and regeneration temperature decreases. The minimum supply air temperature of about 17.5 °C was calculated at a rotational speed for DW from 8 to 10 turns per hour. Narayanan et al. [124] tested an EW coupled with DW, evaporative cooling, and SW. The configuration was simulated in subtropical and tropical climates and was found to perform best in subtropical climates with thermal comfort being met for 93% of the operating hours. For tropical climates, the configuration performed less favorably with only 54% to 63% of operating hours meeting the thermal comfort. Electrical COP of the systems ranged from 2.9 to 4.8 while thermal COP ranged from 0.21 to 0.36 with the lower values for the tropical climate.

Delfani and Karami [125] proposed and modeled three configurations using DW, M−cycle, and heat wheel for different climate conditions. The first configuration consisted of DW and two direct evaporative coolers; one in the supply duct and another in the return duct. The second configuration had DW, M−cycle, and heat wheel. The third one had an additional M−cycle in the return duct. A solar air heater was used for the regeneration process in the three configurations. The transient simulation from June to November showed that the required regeneration temperature is lower in the hot climate. The systems were concluded to be suitable for hot and semi-humid climates. The third arrangement had the highest thermal COP of 0.728 owing to the lower regeneration temperature used in the desiccant wheel. For the dual M−cycle, the thermal COP reduced by nearly 53% when the regeneration temperature changed from 100 to 120 °C. Lee et al. [126] developed 1-D steady-state model to investigate the performance of three different desiccant cooling systems having a sensible heat exchanger: DEC (DEC + desiccant rotor), IEC (IEC + desiccant rotor), and hybrid VCC-DW system. Hybrid VCC-DW was proposed in this study to overcome the limited capacity of DEC and IEC in hot and humid conditions. However, the total COP of IEC was higher than that of Hybrid VCC-DW when the outdoor temperature is less than 35 °C, while the opposite behavior was observed for outdoor temperature more than 40 °C. DEC was suitable when the outdoor temperature is less than 35 °C. Hybrid VCC-DW was preferable when the outdoor temperature is more than 40 °C. The total COP of Hybrid VCC-DW system was higher than that of other systems regardless of the outlet relative humidity. The total COP values of DEC and IEC were almost constant at different outdoor RH. The total COP of DEC was lower than that of IEC systems.

For utilizing solar energy, Li et al. [127] built and tested a solar-assisted SSLC system that comprised two-stage DW and three ECs. The thermal COP was 0.95 in hot and humid climate conditions, while the total COP was 0.45. Zeng et al. [128] optimized the components of this system. The year-round behavior was simulated using TRNSYS. The optimized total COP was 0.85, and the cooling power was 2005 kWh to maintain a room temperature of 24.3 °C. Saghafifar and Gadalla [129] assessed performance of M−cycle and solid desiccant system coupled with PV/T panels for cooling applications in humid climates like UAE. Based on the location of the mixing box, two arrangements were investigated and studied numerically. A seasonal analysis was made to test the behavior of the suggested systems during summer days in Abu Dhabi. The average thermal COP of the two systems was 0.25 and 0.27, while the solar energy shares in regeneration energy are 32.2% and

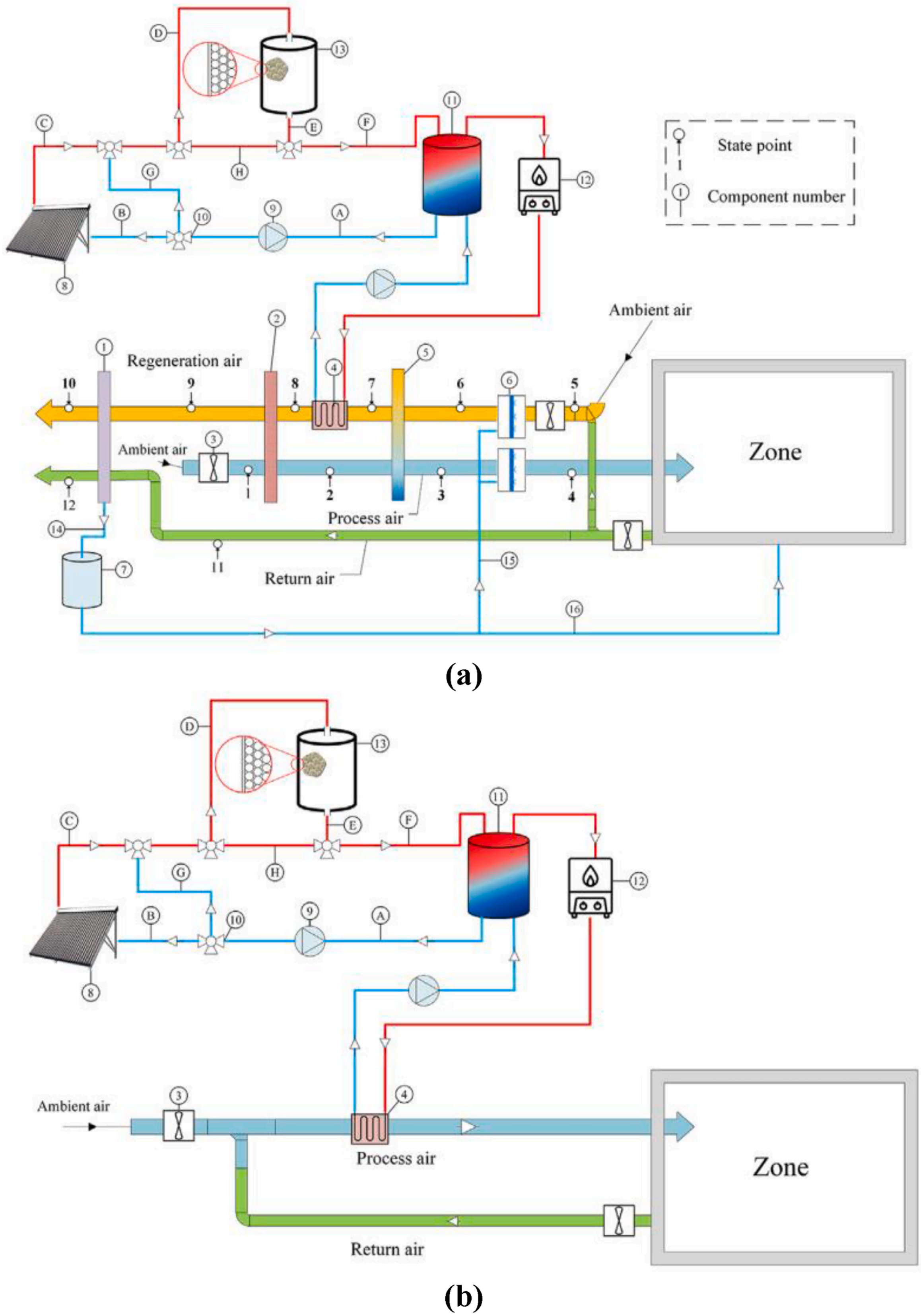

Fig. 12. Schematic diagram of SSLC system for (a) cooling and (b) heating mode [134]

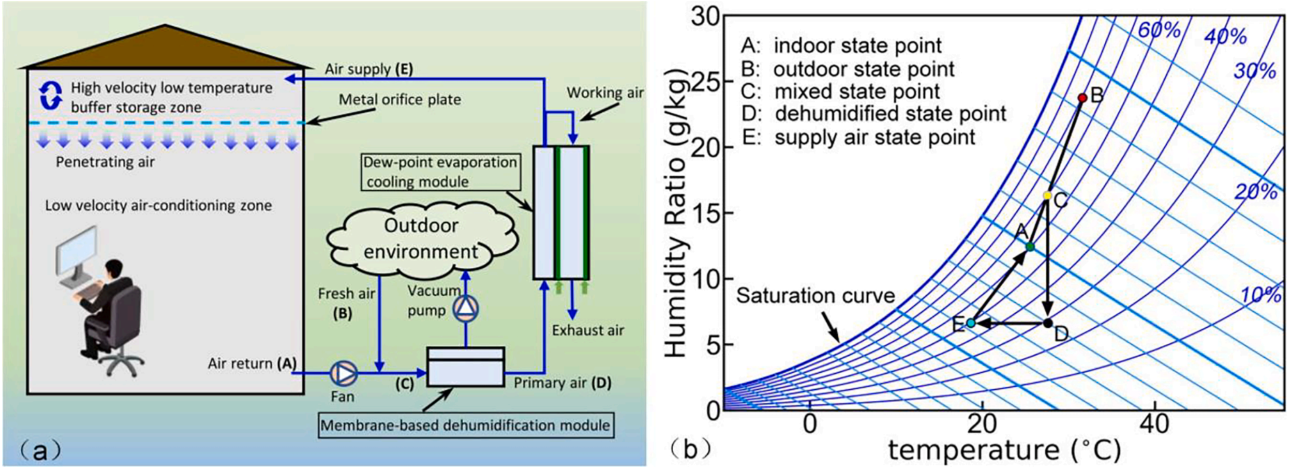

Fig. 13. Schematic of (a) cooling system and (b) processes representation on psychrometry [140]

36.5%, respectively. The configuration with higher thermal COP had less solar collector area of 656 m^2.

Chaudhary et al. [130] proposed a solar cooling unit in which solid DW handled the latent heat, M−cycle removed the sensible load, and hot water from the evacuated tube solar collector regenerated the DW. The system was tested experimentally in Pakistan from May to July. The experimental measurements indicated that the system could handle an average cooling load of 3.78 kW at a thermal COP of 0.91. Heidari et al. [131] modeled EC and silica gel DW cycle in which an evacuated tube solar collector powered the system. The cooling effect was delivered to space while freshwater was produced as a by-product. The system delivered 585 L of water per week, part of this water was used to facilitate the working of EC. The average total COP was estimated to be 1.53, compared with 1.2 for VCC. Compared to VCC, the proposed system consumed 60% less electricity and reduced CO_2 emissions by 18.7% on an integrated monthly result. This resulted in a 3-year payback period. Farooq et al. [132] modeled 3 SSLC configurations in TRNSYS using ECs and DW with auxiliary VCC under Lahore, Pakistan climate conditions. PV/T panels powered the investigated systems. An additional heater was used to heat the regeneration return air in configuration 1 and heated water of the solar heater in configuration 2 and 3 to reach the required regeneration temperature. In configuration 3, the EC was removed which caused an increase in energy consumption with reduced water consumption. Configuration 1 outperformed the other configurations in terms of energy-saving and solar fraction.

Song and Sobhani [133] studied numerically an integrated system of crossflow M−cycle in the supply and return duct and DW. A PVT solar system with Phase Change Material (PCM) was used to produce thermal and electrical energy to heat air for the regeneration process of DW. The optimal regeneration temperature where a maximum thermal COP of 0.415 was achieved was about 70 °C. The maximum thermal exergetic COP was 1.3. Saedpanah and Pasdarshahri [134] proposed an SSLC system that produced water for EC device and worked for cooling and heating, as shown in Fig. 12. In the cooling mode, the system had DW, EC, and heat wheel. They used solar energy to facilitate the regeneration process. In the heating mode, the thermal energy from the solar collector was used to heat the supply air before entering space. A mathematical model was built to simulate the system. It was found that the system could harvest 70% more water from the atmosphere than that required for system operation. It was concluded that the proposed system could replace the conventional VCC with a significant reduction in CO_2 emissions. This study did not present the COP of the system.

Rayegan et al. [135] performed dynamic simulation and multi-objective optimization for hybrid solar-assisted DW with cooling cycle and DEC. The system consisted of a solar-assisted desiccant wheel coupled with a heat recovery wheel, ground-source cooling cycle and DECs. The study aimed to maximize the thermal comfort index and solar contribution and minimize the regeneration temperature. The average electrical COP was estimated to be 10.2 at a thermal comfort index of 95%. The system's payback period was estimated at 5.7 years. Kousar et al. [136] performed a techno-economic assessment of several solar-assisted desiccant cooling units. The solar water heating system provided hot water at 70 °C to regenerate the DW. Either direct or indirect evaporative cooler was used to handle the sensible heat. The systems handled a cooling load of 5.26 kW. The system having a counter-flow indirect evaporative cooler showed the best performance with a thermal COP of 1.85 and an electrical COP 3.9 with an energy cost of 62.9% less than the conventional unit. Thus, the designed systems were more economical than conventional ones.

Zhou et al. [137] researched a system with a crossflow M−cycle and DW driven by hot water from a solar collector. An independent temperature and humidity control system set the room temperature around 23 °C by switching between the cooling and heating modes. TRNSYS simulations were used to study the system's behavior under tropical, subtropical, and temperate climates in Australia. In a tropical climate, the proposed system could not achieve thermal comfort. However, it proved to be adequate in subtropical and temperate climates. This proposed system resulted in 50% energy reduction compared with the conventional HVAC system.

Membranes has also been coupled with evaporative cooling for SSLC. El-Dessouky et al. [138] studied numerically a system in which outdoor air was processed through a membrane dehumidifier, an IEC, and a DEC in sequence. The system operated at relative humidity values less than 30% and temperature more than 35 °C. The results concluded that the proposed integrated system installed in Kuwait could result in 86.2% energy savings compared with VCC. Lin et al. [139] studied a counter-flow dew point EC combined with membrane dehumidification (MD). The system delivered cool and dry air at 18.2 °C dry-bulb temperature and 8.2 g/kg absolute humidity (62.8% RH) at hot and humid conditions. Chun et al. [140] proposed a new cooling system with a total cooling load of 3.5 kW that consisted of dew point EC and VMD, as illustrated in Fig. 13. A thermodynamic model was built and validated to investigate the applicability of the system. The ventilation ratio was investigated, and the optimum value was found in the range of 0.2 to 0.4 where fresh air of 300 m^3/hr was supplied to the space. The electrical COP declined monotonically as the ambient temperature increased. Electrical COP of about 5–7 and 3.5–9 was predicted for Singapore and Changsha, respectively.

4. Primary coefficient of performance

As previously discussed, the SSLC system could be powered by

Table 4
The COP_p of SSLC systems based on vapor compression cycle.

System configuration	Ref.	Methodology	COP_p*	Capacity kW	SHF	Indoor Conditions		Outdoor Conditions		Remarks
						T °C	RH %	T °C	RH %	
Dual VCC	[40]	Modelling	1.92–2.04	100	0.7	27	50	35	44	
	[41]	Modelling (EES)	1.48–1.55	3.5	0.3–1.0	24	50	35	50	
	[42,43]	Experimental	2.51	8.8	–	27	47	35	40	
	[45]	Experimental	1.56	4.4	–	–	–	–	–	
	[46]	Modelling	1.63 – 2.47	1–5.5	–	26	50	26–40	60–80	
	[47]	Modelling	1.41 – 1.48	–	–	25	60	35	61	Total return air
			1.47 – 1.53							15% fresh air
			1.60 – 1.66							15% fresh air with precooling
	[48]	Modelling	1.63 – 1.94	–	–	25	50	32	40–90	
	[49]	Experimental	0.85 – 1.97	5.8–15	–	20–28	40–65	28–36	–	
VCC-DW	[56]	Modelling	1.92	5.4	–	–	–	–	–	
		Experimental	1.83	5.4	–	–	–	–	–	
	[58]	Experimental	0.51	30	–	27	52	30	62	
	[60]	Experimental	1.05 – 1.29	3.6	0.8	27	50	35	44	Refrigerant is CO_2
			1.48 – 1.86							Refrigerant is R410A
	[62]	Modelling	1.20 – 1.73	3.5	0.71	27	50	35	44	Refrigerant is R410A
			0.91 – 1.79							Refrigerant is CO_2
	[65]	Experimental	0.65–0.79	1.9–2.4	–	26	52	28–40	–	
	[66]	Experimental	1.52–1.79	5.5	0.16	27	47	30–35	48–74	
	[68]	Modelling (TRNSYS)	1.39–2.07	1.8	–	25	45	30–41	10–60	
	[69]	Experimental	0.88–0.93	–	–	26	58	28–34	48–83	
	[70]	Modelling	0.81	4	0.79	25	45	–	–	
	[71]	Experimental & modelling	0.96–1.32	3.4–5.4	–	25–26	50	21–38	40–92	
	[73]	Experimental & Modelling	0.76–1.22	2.2–2.7	0.73–0.87	–	–	–	–	
	[74]	Modelling	1.27	–	–	–	60	–	–	
VCC-desiccant coated HX	[72]	Experimental	2.36	7	–	25	–	35	60	30% fresh air
Solar-assisted VCC-DW	[75]	Experimental	1.55–1.82	60	0.48–1.0	26	–	34	65	
	[77]	Modelling (TRNSYS)	0.6	–	–	–	–	–	–	Total fresh air
			0.63							DC driver with total fresh air
			0.74							DC driver power by PVT panels with total fresh air
			0.49							DC driver power by PV panels with total return air
			0.54							DC driver power by PVT panels with total return air
	[78]	Modelling (TRNSYS)	0.39–0.42	32–40	0.59–0.68	22–24	54–56	33	71	
	[79]	Experimental	1.13	30.5	0.6	27	50	34–46	55–70	
	[80]	Modelling (TRNSYS)	0.26	–	–	–	–	–	–	
	[83]	Experimental	0.27–0.36	–	–	–	–	28–33	73–78	
	[84]	Modelling	0.40–1.15	6.8–14	–	–	50–60	–	–	Changing return air ratios
VCC-LD	[88]	Experimental and Modelling	0.85–1.03	2.6–5.1	–	–	–	27–35	40–50	
			0.94–1.10	2.6–5.1						Evaporative cooling is used
	[89]	Experimental	2.39–2.77	40.8–47	–	23–26	62–72	29–30	76–85	Total fresh air
	[91]	Experimental & modelling	1.03	–	–	–	–	–	–	
	[92]	Experimental	1.52	509	–	24–27	43–67	20–31	60–90	
	[95,96]	Modelling	0.57–1.25	27	0.83	27	47	28–37	41	
	[97]	Modelling	0.55–0.64	–	–	–	–	–	–	
	[99]	Modelling (MATLAB)	1.9	29.7	–	–	–	35	56	Total Fresh air
	[100]	Modelling (MATLAB)	1.52–2.81	–	–	–	–	30–35	48–78	Total Fresh air
	[102]	Experimental	0.67–0.82	5	–	–	–	35–38	55–65	Total Fresh air
	[104]	Experimental	1.37	232–695	0.41	–	–	23.5–34.4	55–90	Total Fresh air
	[105]	Experimental	0.86	7.5	–	–	–	–	–	
VCC-AB	[107]	Modelling	0.67–0.78	100	0.7	24	50	35	70	
VCC-MD	[109]	Modelling	1.63	10.6	–	–	–	–	–	

Table 5
The COP_p of SSLC systems based on non-vapor compression cycle.

System configuration	Ref.	Methodology	Primary COP*	Capacity kW	SHF	Indoor Conditions		Outdoor Conditions		Remarks
						T °C	RH %	T °C	RH %	
Solar-assisted AB-DW	[77]	Modelling (TRNSYS)	0.22	–	–	–	–	–	–	Total return air
AD	[111]	Modelling	0.50–0.78	–	–	–	–	–	–	
AB-DW	[113]	Modelling (TRNSYS)	1.52	16.6	0.75	23–24	–	30–41	–	
EC-DW	[117]	Experimental	0.57	–	–	–	–	30	71	Total Fresh air
IEC-LD	[118]	Experimental	0.41	–	–	–	–	34–35	50–70	Total Fresh air
EC-SW-DW	[120]	Exp. & modelling	0.59	14.3	–	27	50	35	40	
DEC-EW-DW	[124]	Modelling (TRNSYS)	0.18–0.30	–	–	26	50	22–36	40–91	
Mcycle-EW-DW	[125]	Modelling (TRNSYS)	0.33–0.56	1.3	–	26	–	25–45	–	
DEC-Mcycle-EW-DW			0.28–0.51	1.4						
2Mcycle-EW-DW			0.50–0.73	1.8						
DEC-SW-DW	[126]	Modelling	0.14–0.22	3.6–6.3	–	–	–	25–50	4–98	30% fresh air
EC-SW-DW			0.19–0.48	3.9–7.1						
EC-VCC-DW			0.18–0.60	3.8–7.3						
Solar-assisted DEC-DW	[127]	Experimental	0.66	4–5.1	–	25	70	25–33	–	
Solar-assisted DEC-DW	[128]	Modelling (TRNSYS)	0.45	0.7	–	25–30	55–70	32–41	60–78	
Solar assisted Mcycle-SW-DW	[129]	Modelling	0.25	100	–	24	50	23–42	30–85	
			0.27	100	–	24	50	23–42	30–85	Total return air
Solar-assisted Mcycle-DW	[130]	Experimental	0.65–1.17	3.4–4.3	–	–	–	27–40	–	Total fresh air
Solar-assisted Mcycle-DW	[133]	Modelling	0.39	13.5–18.7	–	22	50	30–33	64–69	
Solar-assisted 2DEC-SW-DW	[136]	Experimental	0.24–0.39	2.7	0.66	–	–	27–41	23–73	Total fresh air
Solar-assisted Mcycle-DEC-SW-DW			0.37–0.49	3.4	0.58			28–40	22–70	
Solar-assisted 2Mcycle-SW-DW			0.68–0.78	5.6	0.49			28–39	24–70	
EC-MD	[140]	Modelling	2.36	3.5	0.57	26	60	–	–	30% fresh air

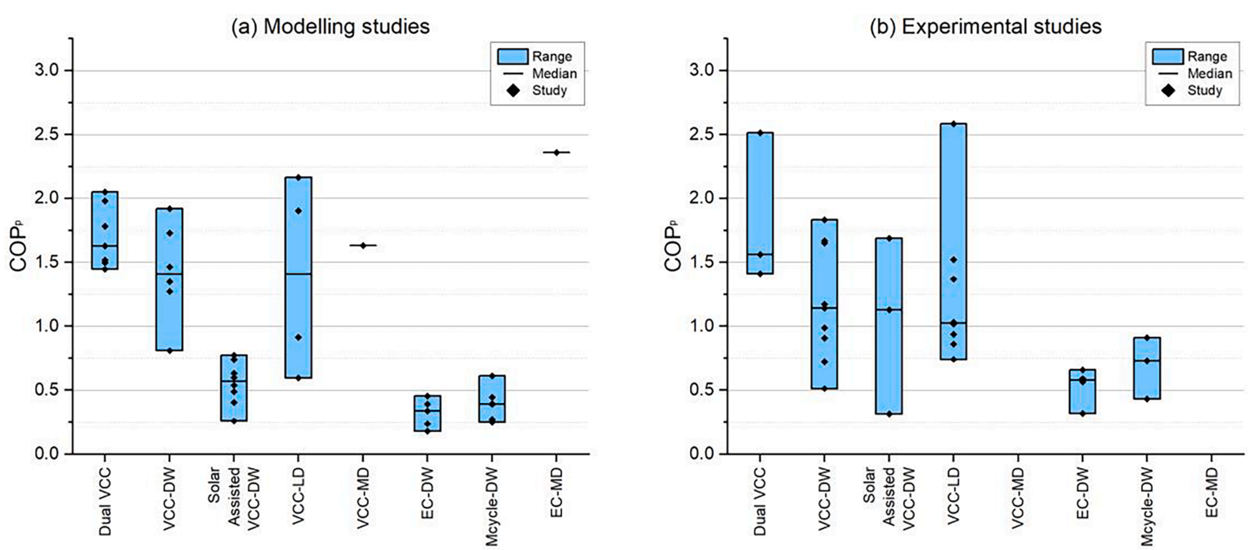

Fig. 14. COP_p ranges for different configurations based on reviewed literature with conversion factor of 38%: (a) Modelling studies (b) Experimental studies.

electrical or thermal energy. In order to establish a fair comparison among several cooling technologies driven by different energy sources, a unified evaluation parameter should be used. In this paper, primary COP (COP_p) is defined as presented in Eq. (1), and used to establish a fair comparison of the different SSLC systems.

$$COP_p = \frac{\dot{Q}_c}{\dot{Q}_{th} + \frac{\dot{W}_{elec}}{f}} \tag{1}$$

where $\dot{Q}_c$ is the cooling capacity of the system, $\dot{Q}_{th}$ is thermal energy consumption, $\dot{W}_{elec}$ is electrical energy consumption, and f is a conversion factor that is used to convert electrical energy consumption to primary energy consumption. This equation assumes that the thermal energy conversion factor to primary energy is 1.0.

The conversion factor is the average electric power grid efficiency that is determined based on the energy mix including coal, petroleum, natural gas, or nuclear energy source. Based on the available data in the USA [141], the conversion factor is estimated to be 38%. Therefore, the primary COP of SSLC systems reviewed in the present work is estimated and listed in Table 4 and Table 5.

For different combinations of sensible and latent cooling technolgies, different ranges of COP_p exist based on the corresponding efficiency of each technology and the operating conditions. Fig. 14 shows the range, median and specific values of COP_p for each configuration based on our review.

SSLC systems based on VCC had higher COP_p values than ones based on non-VCC. This is owing to the higher COP of VCC, which enhances the overall performance of the systems. The dual VCC configuration showed COP_p ranged from 1.45 to 2.05 for modelling studies with a median of 1.63 and from 1.41 to 2.51 with a median of 1.56 for experimental studies, depending mostly on the compressor isentropic efficiency and operating indoor and outdoor conditions. Using high efficiency compressors directly increased the COP_p of the dual VCC systems. Coupling VCC with DW showed lower COP_p values than dual VCC. The COP_p ranged from 0.26 to 1.92 with a median of 0.76 for modelling studies and from 0.31 to 1.83 with a median of 1.13 for experimental studies. The COP_p of such systems increases when the heat of condensation, or a portion of it, is recovered and used for the DW regeneration. However, the required regeneration temperature may raise a concern about whether the heat rejected from the condenser is suitable to be used or not. The performance of such systems would increase significantly by lowering the regeneration temperature without affecting the performance of the DW. Also, the COP_p of the hybrid VCC-DW systems increases when the system is used in humid conditions. A VCC coupled with LD showed the highest range of the COP_p from 0.6 to 2.17 with a median of 1.41 for modelling studies and from 0.74 to 2.58 with a median of 1.02 for experimental studies, because the LD could be regenerated using the VCC's heat of condensation. However, the LD carry-over raises health concerns that should be considered. VCC coupled with coated desiccant material showed a high value of COP_p of 2.36 based on an experimental study; This configuration inherits the merits of using VCC with high evaporating temperature, with little increase in energy consumption due to the slight increase in fan power of heat exchangers. Other configurations that incorporated VCC showed a subpar performance with a range of COP_p from 0.73 to 1.63 with a median of 1.18 for modelling studies.

SSLC systems based on sorption technology to handle sensible load have not been investigated enough in literature to get an overview of its potential. On the other hand, EC has been covered intensively in literature, especially integrating DEC, IEC, or M−cycle with DW, LD, or MD. EC coupled with DW, or LD showed a low range of COP_p from 0.18 to 0.613 with a median of 0.39 for modelling studies and from 0.32 to 0.91 with a median of 0.59 for experimental studies. This low range is because no heat can be harvested to regenerate the desiccant material, and an external heat source should be used. EC coupled with MD has not been covered enough in the literature, and the available study had a value of COP_p of 2.36 based on a modelling study.

5. Challenges and opportunities

Different configurations of the SSLC systems were proposed and tested in literature. However, system-level engineering of SSLC systems is lacking, and it still needs further research and development to transform SSLC systems for commercialization. Optimizing the control system of temperature and humidity is a challenge to minimize load while maintaining indoor thermal comfort. Another challenge facing this technology is proposing an efficient and compact system to be an alternative to traditional VCC. Among many SSLC systems reviewed in this paper, the hybrid VCC and desiccant systems have a good potential to achieve high efficiency and reliable operation. The performance of this integration depends mainly on the efficiency of the desiccant dehumidification cycle, which is low due to challenges at the material and system level. At the material level, efficient adsorbent material should be developed to advance this technology. Metal-organic frameworks (MOFs) are promising nano-porous adsorbents due to their high adsorption capacity. Therefore, experimental tests should be conducted to evaluate SSLC systems using MOFs. Along with designing and optimizing efficient heat and mass exchangers, a significant reduction in the capital and running cost of the SSLC system could be achieved. Regeneration of desiccant material is an energy-intensive process. Therefore, there is an urgent need to develop an efficient regeneration process. These efforts could contribute to development at the system level.

The membrane-based dehumidification system has a promising thermodynamic performance. However, many challenges should be addressed to commercialize it, such as developing highly efficient vacuum pump, proposing an accurate control system to improve the system reliability, and solving the issues related to membrane fouling. The water vapor pressure in the supply air channel must be specified carefully for appropriate driving force. Another challenge is the difficulty of filtering the air from airborne particulates, such as dust, which increases flow resistance and hence power consumption. Moreover, the membrane selectivity would still allow for other molecules, although a small fraction, to pass through along with water vapor. This negatively affect the pressure in the vacuum side. These challenges should be addressed to make membrane dehumidification more reliable and attractive for future use.

To ensure that sensible or latent are handled most effectively, it is important to understand the related capital and operating (non-energy) costs, and the typical maintenance of the selected technology. VCC is a mature technology that offers the highest system reliability and lowest capital cost. Furthermore, typical VCC systems require little maintenance during operation. On the other hand, membrane dehumidification technology is an emerging technology that has been recently employed for air-conditioning. It requires the highest total cost (mostly being capital costs) and low maintenance. Absorption cooling technology involves more components and large equipment size, this results in high

Table 6
Operating (non-energy) cost, capital cost and typical maintenance for each cooling technology.

Technology	Indicative capital cost	Indicative operating cost (non-energy)	Typical maintenance
VCC	$	$	• Filters change • Refrigerant recharge • Condenser(s)/ Evaporator(s) cleaning
AB	$$$	$$	• Chemical treatment adjustments • Valves and fittings maintenance and replacements • Burner maintenance • Heat exchangers cleaning • Descaling • Filters change • Vacuum maintenance • Pumps maintenance and replacements • Fans maintenance and replacements
AD	$$$	$$	• Heat exchangers cleaning • Valves and fittings maintenance and replacements • Burner maintenance • Vacuum maintenance • Pumps maintenance and replacements • Fans maintenance and replacements
EC	$$	$$$	• Water nozzles cleaning • Water lines cleaning • Water treatment
DW	$$	$$	• Rotating wheel cleaning • Belts and motors maintenance
LD	$$$	$$	• Liquid desiccant recharge • Desiccant towers cleaning • Fans maintenance and replacements
MD	$$$	$$	• Membrane cleaning • Vacuum pump maintenance and replacements • Fans maintenance and replacements

$: low indicative cost, $$: medium indicative cost, $$$: high indicative cost

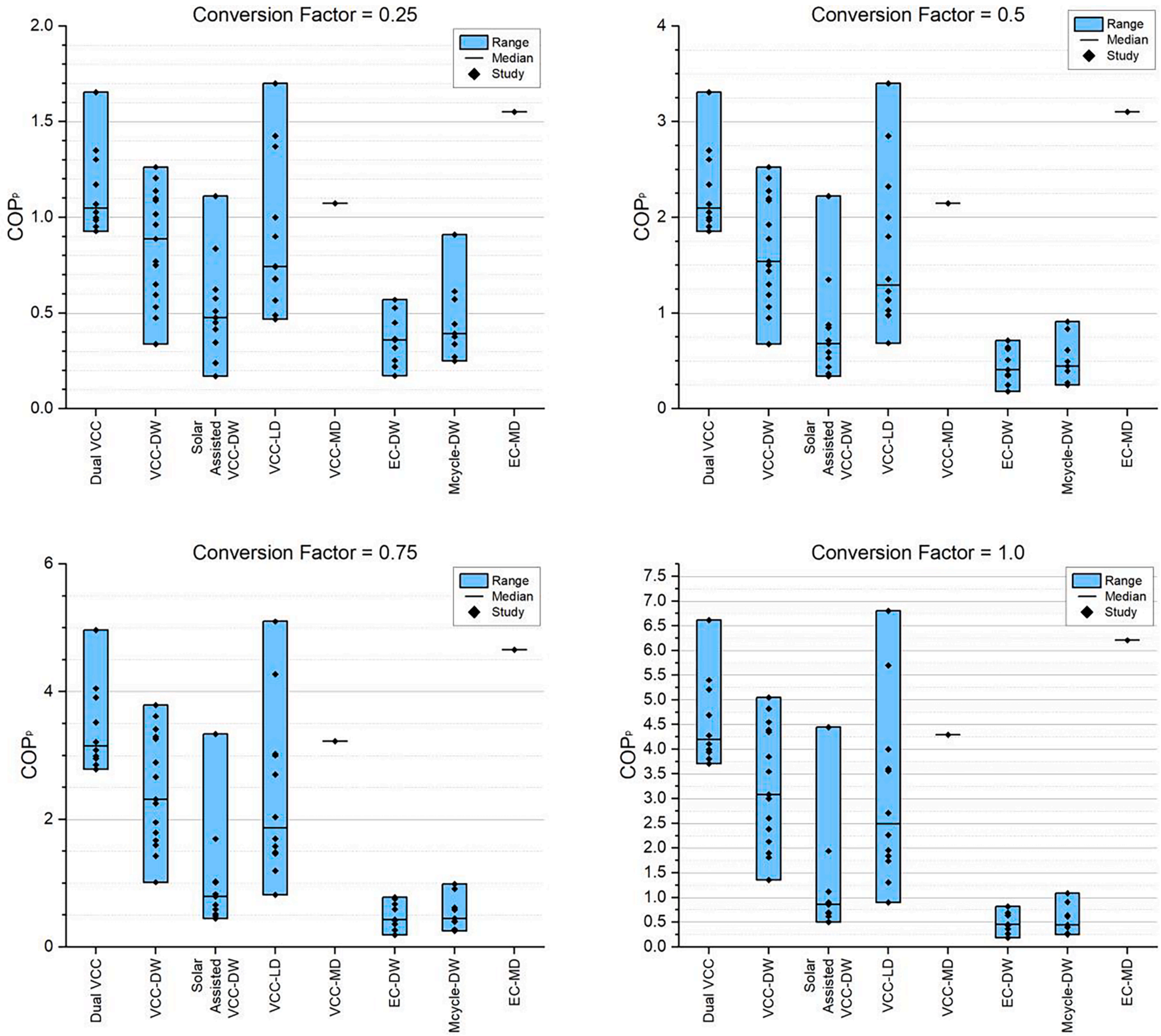

Fig. 15. Effect of conversion factor on COP_p of different configurations.

capital costs and requires significant maintenance costs. Auxiliaries such as SW and EW, added to the different configurations, would also increase the capital and operating costs, and would require additional maintenance. There is a trade-off between energy efficiency and total indicative cost that these auxiliaries offer. Indicative capital cost, indicative operating cost and typical maintenance of each technology are shown in Table 6.

The energy mix has a significant effect on COP_p. With the increased penetration of renewable and sustainable energy resources, the electric conversion factor could approach 1.0. The impact of the electric conversion factor on the COP_p is presented in Fig. 15. As demonstrated, higher conversion factors will further the advantage of VCC based SSLC technologies over evaporative cooling technologies.

6. Conclusion

Independent control of air temperature and humidity has been proven as an efficient way to achieve thermal comfort in occupied zones. SSLC technology is an emerging air conditioning technology that allows for independent control of air temperature and humidity at improved efficiency compared with conventional systems. This review paper summarizes recent findings from more than 100 papers listing alternative SSLC configurations along with either numerical or experimental studies. It also presents the current advances in different configurations of SSLC systems. We used the primary COP to compare between the different SSLC technologies to consider both thermal and electrical energy sources fairly. It is concluded that the highest primary COP is estimated to be about 2.58 for VCC coupled with LD due to the high COP of VCC and low regeneration temperature of LD that is using the VCC heat of condensation. It is noticed that the VCC is widely used to handle the sensible load; however, its size should be selected precisely based on local climate conditions to achieve higher primary COP and save cost. The current state-of-the-art sorption cycles and evaporative coolers cannot compete with VCC in handling the sensible heat due to their low efficiency, high cost, and large size. Therefore, research and development should focus on developing efficient heat exchangers (which is the main core of these cycles), aiming to reduce the dimensions and capital costs.

Handling the latent load is a key process in SSLC system. DW is a promising technology for handling the latent load of buildings in hot and humid areas. However, new efficient desiccant materials with low cost need to be sought. Also, regeneration energy, system size, and capital cost are the main challenges that need to be addressed to advance this technology. Advanced desiccant materials should be developed to improve the capacity of the desiccant dehumidification systems. Solar energy is found to be a suitable energy resource for driving the desiccant regeneration within the SSLC system. Also, using the VCC desuperheater or heat of condensation is proven to improve the primary COP. In general, there is an urgent need for more experimental and theoretical works to achieve further development in SSLC systems based on non-VCC at the material and system level.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

This work is part of project No. 3988 funded by the office of sponsored research at King Abdullah University of Science and Technology (KAUST). We would like to acknowledge the support from Dr. Rory Jordan at KAUST.

References

[1] U.S. Department of Energy, Buildings energy databook, Energy Efficiency & Renewable Energy Department. (2012) 286. http://buildingsdatabook.eren.doe.gov/DataBooks.aspx.
[2] IEA, The Future of Cooling, IEA, Paris, 2018. https://www.iea.org/reports/the-future-of-cooling.
[3] Harriman LG, Plager D, Kosar D. Dehumidification and cooling loads from ventilation air. Energy Eng 1999;96:31–45. https://doi.org/10.1080/01998595.1999.10530479.
[4] Son W, Nagai H. Reducing effect of latent heat load by fresh air heat load reduction system using underground double floor space. J Asian Architect Build Eng 2004;3(2):253–8. https://doi.org/10.3130/jaabe.3.253.
[5] IEA, Energy Technology Perspectives, 2020. https://www.iea.org/reports/energy-technology-perspectives-2020.
[6] Davis LW, Gertler PJ. Contribution of air conditioning adoption to future energy use under global warming. PNAS 2015;112(19):5962–7. https://doi.org/10.1073/pnas.1423558112.
[7] Liu X, Jiang Y, Zhang T, Temperature and humidity independent control (THIC) of air-conditioning system, 2013. doi:10.1007/978-3-642-42222-5.
[8] Wolkoff P. Indoor air humidity, air quality, and health – An overview. Int J Hyg Environ Health 2018;221(3):376–90. https://doi.org/10.1016/j.ijheh.2018.01.015.
[9] Clements N, Binnicker MJ, Roger VL. Indoor environment and viral infections. Mayo Clin Proc 2020;95(8):1581–3. https://doi.org/10.1016/j.mayocp.2020.05.028.
[10] Arundel AV, Sterling EM, Biggin JH, Sterling TD. Indirect health effects of relative humidity in indoor environments. Environ Health Perspect 1986;65:351–61. https://doi.org/10.1289/ehp.8665351.
[11] Gluesenkamp KR, Nawaz K. Separate sensible and latent cooling: carnot limits and system taxonomy. Int J Refrig 2021. https://doi.org/10.1016/j.ijrefrig.2021.02.019.
[12] Jani DB, Mishra M, Sahoo PK. A critical review on solid desiccant-based hybrid cooling systems. Int J Air-Conditioning Refrig 2017;25. https://doi.org/10.1142/S2010132517300026.
[13] Mujahid Rafique M, Gandhidasan P, Rehman S, Al-Hadhrami LM. A review on desiccant based evaporative cooling systems. Renew Sustain Energy Rev 2015;45:145–59. https://doi.org/10.1016/J.RSER.2015.01.051.
[14] Constantino MC, Kanizawa FT. Evaluation of pressure drop effect on COP of single-stage vapor compression refrigeration cycles. Thermal Sci Eng Prog 2021. https://doi.org/10.1016/j.tsep.2021.101048.
[15] Park C, Lee H, Hwang Y, Radermacher R. Recent advances in vapor compression cycle technologies. Int J Refrig 2015;60:118–34. https://doi.org/10.1016/j.ijrefrig.2015.08.005.
[16] Vallès M, Bourouis M, Boer D. Solar-driven absorption cycle for space heating and cooling. Appl Therm Eng 2020;168. https://doi.org/10.1016/j.applthermaleng.2019.114836.
[17] Abid M, Khan MS, Ratlamwala TAH, Malik MN, Ali HM, Cheok Q. Thermodynamic analysis and comparison of different absorption cycles driven by evacuated tube solar collector utilizing hybrid nanofluids. Energy Convers Manage 2021;246:114673. https://doi.org/10.1016/j.enconman.2021.114673.
[18] Srikhirin P, Aphornratana S, Chungpaibulpatana S. A review of absorption refrigeration technologies. Renew Sustain Energy Rev 2001;5(4):343–72. https://doi.org/10.1016/S1364-0321(01)00003-X.
[19] Critoph RE. Forced convection adsorption cycles. Appl Therm Eng 1998;18(9-10):799–807.
[20] Wang DC, Li YH, Li D, Xia YZ, Zhang JP. A review on adsorption refrigeration technology and adsorption deterioration in physical adsorption systems. Renew Sustain Energy Rev 2010;14(1):344–53. https://doi.org/10.1016/j.rser.2009.08.001.
[21] Yang H, Shi W, Chen Y, Min Y. Research development of indirect evaporative cooling technology: an updated review. Renew Sustain Energy Rev 2021;145. https://doi.org/10.1016/j.rser.2021.111082.
[22] Porumb B, Ungureşan P, Tutunaru LF, Şerban A, BĂlan M. A review of indirect evaporative cooling operating conditions and performances. Energy Procedia 2016;85:452–60. https://doi.org/10.1016/j.egypro.2015.12.226.
[23] Mahmood MH, Sultan M, Miyazaki T, Koyama S, Maisotsenko VS. Overview of the Maisotsenko cycle – a way towards dew point evaporative cooling. Renew Sustain Energy Rev 2016;66:537–55. https://doi.org/10.1016/J.RSER.2016.08.022.
[24] Kim KJ, Feldman Jr KT, Lloyd G, Razani A. Compressor-driven metal-hydride heat pumps. Appl Therm Eng 1997;17(6):551–60. https://doi.org/10.1016/S1359-4311(96)00067-1.
[25] Zhao D, Tan G. A review of thermoelectric cooling: materials, modeling and applications. Appl Therm Eng 2014;66(1-2):15–24. https://doi.org/10.1016/j.applthermaleng.2014.01.074.
[26] Aimi M, Arik M, Bray J, Gorczyca T, Michael D, Weaver S, Thermotunneling Based Cooling Systems for High Efficiency Buildings, Pittsburgh, PA, and Morgantown, WV (United States), 2007. doi:10.2172/921025.
[27] Yu BF, Gao Q, Zhang B, Meng XZ, Chen Z. Review on research of room temperature magnetic refrigeration. Int J Refrig 2003;26(6):622–36. https://doi.org/10.1016/S0140-7007(03)00048-3.
[28] Bansal P, Vineyard E, Abdelaziz O. Status of not-in-kind refrigeration technologies for household space conditioning, water heating and food refrigeration. Int J Sustain Built Environ 2012;1(1):85–101. https://doi.org/10.1016/j.ijsbe.2012.07.003.
[29] UNEP Technical Options Committee, 2018 Report of the Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee, 2019. https://ozone.unep.org/sites/default/files/2019-04/RTOC-assessment-report-2018_0.pdf.
[30] Hamed AM, Khalil A, Kabeel AE, Bassuoni MM, Elzahaby AM. Performance analysis of dehumidification rotating wheel using liquid desiccant. Renewable Energy 2005;30(11):1689–712. https://doi.org/10.1016/j.renene.2004.11.014.
[31] Elsarrag E. Performance study on a structured packed liquid desiccant regenerator. Sol Energy 2006;80(12):1624–31. https://doi.org/10.1016/j.solener.2005.11.005.
[32] Li Z, Liu X, Jiang Yi, Chen X. New type of fresh air processor with liquid desiccant total heat recovery. Energy Build 2005;37(6):587–93. https://doi.org/10.1016/j.enbuild.2004.09.017.
[33] Daou K, Wang R, Xia Z. 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.
[34] N.A. Pennington, Humidity Changer For Air Conditioning, US2700537A, 1955.
[35] Dunkle RV. A method of solar air conditioning. Mech Chem Eng Trans I.E. Aust. 1965;MC1:73.
[36] Maclaine-Cross IL, Banks PJ. A General theory of wet surface heat exchangers and its application to regenerate evaporative cooling. J Heat Transfer 1981;103:579–85. https://doi.org/10.1115/1.3244505.
[37] Jain S, Dhar PL, Kaushik SC. Evaluation of solid-desiccant-based evaporative cooling cycles for typical hot and humid climates. Int J Refrig 1995;18(5):287–96. https://doi.org/10.1016/0140-7007(95)00016-5.
[38] Woods J. Membrane processes for heating, ventilation, and air conditioning. Renew Sustain Energy Rev 2014;33:290–304. https://doi.org/10.1016/j.rser.2014.01.092.
[39] Bui DT, Nida A, Ng KC, Chua KJ. Water vapor permeation and dehumidification performance of poly(vinyl alcohol)/lithium chloride composite membranes. J Membr Sci 2016;498:254–62. https://doi.org/10.1016/j.memsci.2015.10.021.
[40] Ling J, Hwang Y, Radermacher R. Theoretical study on separate sensible and latent cooling air-conditioning system. Int J Refrig 2010;33(3):510–20. https://doi.org/10.1016/j.ijrefrig.2009.11.011.
[41] Abdelaziz O. Primary energy efficiency analysis of different separate sensible and latent cooling techniques. In: Refrigeration Science and Technology; 2015. p. 3134–41. https://doi.org/10.18462/iir.icr.2015.0060.
[42] Liu C, Zhang H, Zhang L, Pan J. Development of a novel structure rotary compressor for separate sensible and latent cooling air-conditioning system. Paper 2394. International Compressor Engineering Conference. 2016. https://docs.lib.purdue.edu/icec/2394.
[43] Zhang L, Liu C, Research on the Application of Rotary Compressor with Two Independent Suction Pressures on Fresh Air-Conditioning System, In International Compressor Engineering Conference, 2018: p. Paper 2547. https://docs.lib.purdue.edu/icec/2547.
[44] Liu J, She X, Zhang X, Cong L, Man L, Lindeman B, et al. Experimental and theoretical study on a novel double evaporating temperature chiller applied in THICS using R32/R236fa. Int J Refrig 2017;75. https://doi.org/10.1016/j.ijrefrig.2016.08.015.
[45] Liu J, She X, Zhang X, Man L, Zhou W. Experimental study of a novel double temperature chiller based on R32/R236fa. Energy Convers Manage 2016;124. https://doi.org/10.1016/j.enconman.2016.06.023.
[46] Yang Y, Ren C, Tu M, Luo B, Yang C, Fu J. Performance analysis for a new hybrid air conditioning system in hot-humid climates by simulation. Int J Refrig 2020;117:328–37. https://doi.org/10.1016/j.ijrefrig.2020.05.008.
[47] Chen T, Yin Y, Zhang X. Applicability and energy efficiency of temperature and humidity independent control systems based on dual cooling sources. Energy Build 2016;121. https://doi.org/10.1016/j.enbuild.2016.04.001.

[48] Liu J, Zhang X, Lin Z. Exergy and energy analysis of a novel dual-chilling-source refrigerating system applied to temperature and humidity independent control. Energy Convers Manage 2019;197:111875. https://doi.org/10.1016/j.enconman.2019.111875.
[49] Han X, Zhang Xu. Experimental study on a residential temperature-humidity separate control air-conditioner. Energy Build 2011;43(12):3584–91. https://doi.org/10.1016/j.enbuild.2011.09.029.
[50] Zhang XJ, Xiao F, Li S. Performance study of a constant temperature and humidity air-conditioning system with temperature and humidity independent control device. Energy Build 2012;49:640–6. https://doi.org/10.1016/j.enbuild.2012.03.020.
[51] Ma J, Horton WT. A sequential approach for achieving separate sensible and latent cooling. Int J Refrig 2020;117:104–13. https://doi.org/10.1016/j.ijrefrig.2020.04.004.
[52] Luo WJ, Kuo HC, Wu JY, Faridah D. Development and analysis of a new multi-function heat recovery split air conditioner with parallel refrigerant pipe. Adv Mech Eng 2016;8:1–12. https://doi.org/10.1177/1687814016671444.
[53] Subramanyam N, Maiya MP, Murthy SS. Application of desiccant wheel to control humidity in air-conditioning systems. Appl Therm Eng 2004;24. https://doi.org/10.1016/j.applthermaleng.2004.04.008.
[54] Mohammad AT, Bin Mat S, Sulaiman MY, Sopian K, Al-abidi AA. Survey of liquid desiccant dehumidification system based on integrated vapor compression technology for building applications. Energy Build 2013;62. https://doi.org/10.1016/j.enbuild.2013.03.001.
[55] Burns PR, Mitchell JW, Beckman WA. Hybrid desiccant cooling systems in supermarket applications. ASHRAE Trans 1985;91:457–68.
[56] Jia CX, Dai YJ, Wu JY, Wang RZ. Analysis on a hybrid desiccant air-conditioning system. Appl Therm Eng 2006;26(17-18):2393–400. https://doi.org/10.1016/j.applthermaleng.2006.02.016.
[57] Liu W, Lian Z, Radermacher R, Yao Ye. Energy consumption analysis on a dedicated outdoor air system with rotary desiccant wheel. Energy 2007;32(9):1749–60.
[58] Hürdoğan E, Büyükalaca O, Yılmaz T, Hepbaşlı A. Experimental investigation of a novel desiccant cooling system. Energy Build 2010;42(11):2049–60.
[59] 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. https://doi.org/10.1016/j.rser.2009.07.016.
[60] Ling J, Kuwabara O, Hwang Y, Radermacher R. Experimental evaluation and performance enhancement prediction of desiccant assisted separate sensible and latent cooling air-conditioning system. Int J Refrig 2011;34(4):946–57. https://doi.org/10.1016/j.ijrefrig.2010.12.008.
[61] ANSI/AHRI, AHRI Standard 210/240, (2017). http://www.ahrinet.org/App_Content/ahri/files/STANDARDS/AHRI/AHRI_Standard_210-240_2017.pdf.
[62] Ling J, Kuwabara O, Hwang Y, Radermacher R. Enhancement options for separate sensible and latent cooling air-conditioning systems. Int J Refrig 2013;36(1):45–57. https://doi.org/10.1016/j.ijrefrig.2012.09.003.
[63] Khosravi S, Yau YH, Mahlia TMI, Saidi MH. A new approach to exergy analyses of a hybrid desiccant cooling system compares to a vapor compression system. Appl Mech Mater 2012;110–116:2163–9. https://doi.org/10.4028/www.scientific.net/AMM.110-116.2163.
[64] Bejan A, Tsatsaronis G, Moran MJ. Thermal design and optimization. New York: Wiley; 1996.
[65] Sheng Y, Zhang Y, Deng N, Fang L, Nie J, Ma L. Experimental analysis on performance of high temperature heat pump and desiccant wheel system. Energy Build 2013;66. https://doi.org/10.1016/j.enbuild.2013.07.058.
[66] Jiang Y, Ge TS, Wang RZ, Huang Y. Experimental investigation on a novel temperature and humidity independent control air conditioning system – part I: cooling condition. Appl Therm Eng 2014;73. https://doi.org/10.1016/j.applthermaleng.2014.08.028.
[67] Alabdulkarem A, Cristiano M, Hwang Y, Radermacher R, Design and Testing of a Separate Sensible and Latent Cooling Packaged Terminal Air Conditioning Unit, ASME 2015 9th International Conference on Energy Sustainability, ES 2015, Collocated with the ASME 2015 Power Conference, the ASME 2015 13th International Conference on Fuel Cell Science, Engineering and Technology, and the ASME 2015 Nuclear Forum. 1 (2015). doi:10.1115/ES2015-49065.
[68] Jani DB, Mishra M, Sahoo PK. Performance studies of hybrid solid desiccant–vapor compression air-conditioning system for hot and humid climates. Energy Build 2015;102. https://doi.org/10.1016/j.enbuild.2015.05.055.
[69] Jani DB, Mishra M, Sahoo PK. Experimental investigation on solid desiccant–vapor compression hybrid air-conditioning system in hot and humid weather. Appl Therm Eng 2016;104. https://doi.org/10.1016/j.applthermaleng.2016.05.104.
[70] Lee H, Lin X, Hwang Y, Radermacher R. Performance investigation on solid desiccant assisted mobile air conditioning system. Appl Therm Eng 2016;103:1370–80. https://doi.org/10.1016/j.applthermaleng.2016.05.053.
[71] Nie J, Li Z, Hu W, Fang L, Zhang Q. Theoretical modelling and experimental study of air thermal conditioning process of a heat pump assisted solid desiccant cooling system. Energy Build 2017;153:31–40. https://doi.org/10.1016/J.ENBUILD.2017.07.075.
[72] Tu YD, Wang RZ, Ge TS, Zheng X. Comfortable, high-efficiency heat pump with desiccant-coated, water-sorbing heat exchangers. Sci Rep 2017;7:1(7):1–10. https://doi.org/10.1038/srep40437.
[73] Jani DB, Mishra M, Sahoo PK. Performance analysis of a solid desiccant assisted hybrid space cooling system using TRNSYS. J Build Eng 2018;19:26–35. https://doi.org/10.1016/j.jobe.2018.04.016.
[74] Choi S, Choi S. Desiccant cooling assisted vapor compression system: a double stage desiccant cooling cycle via evaporative condenser. Appl Therm Eng 2021:117456. https://doi.org/10.1016/J.APPLTHERMALENG.2021.117456.
[75] Ma Q, Wang RZ, Dai YJ, Zhai XQ. Performance analysis on a hybrid air-conditioning system of a green building. Energy Build 2006;38(5):447–53.
[76] Beccali M, Finocchiaro P, Nocke B. Energy and economic assessment of desiccant cooling systems coupled with single glazed air and hybrid PV/thermal solar collectors for applications in hot and humid climate. Sol Energy 2009;83(10):1828–46.
[77] 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(12):2386–99.
[78] Fong KF, Lee CK, Chow TT, Fong AML. 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.
[79] La D, Dai Y, Li Y, Ge T, Wang R. 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(11):2997–3009.
[80] Al-Alili A, Hwang Y, Radermacher R, Kubo I. A high efficiency solar air conditioner using concentrating photovoltaic/thermal collectors. Appl Energy 2012;93:138–47. https://doi.org/10.1016/J.APENERGY.2011.05.010.
[81] Hands S, Sethuvenkatraman S, Peristy M, Rowe D, White S. Performance analysis & energy benefits of a desiccant based solar assisted trigeneration system in a building. Renewable Energy 2016;85:865–79. https://doi.org/10.1016/J.RENENE.2015.07.013.
[82] Angrisani G, Roselli C, Sasso M, Tariello F. Dynamic performance assessment of a solar-assisted desiccant-based air handling unit in two Italian cities. Energy Convers Manage 2016;113:331–45. https://doi.org/10.1016/J.ENCONMAN.2016.01.052.
[83] Luo WJ, Faridah D, Fasya FR, Chen YS, Mulki FH, Adilah UN. Performance enhancement of hybrid solid desiccant cooling systems by integrating solar water collectors in Taiwan. Energies. 2019;12:1–18. https://doi.org/10.3390/en12183470.
[84] Liu Y, Chen Y, Wang D, Liu J, Li L, Luo X, et al. Performance evaluation of a hybrid solar powered rotary desiccant wheel air conditioning system for low latitude isolated islands. Energy Build 2020;224:110208. https://doi.org/10.1016/J.ENBUILD.2020.110208.
[85] Mohammad AT, Mat SB, Sulaiman MY, Sopian K, Al-abidi AA. Survey of liquid desiccant dehumidification system based on integrated vapor compression technology for building applications. Energy Build 2013;62:1–14.
[86] Studak JW, Peterson JL, A Preliminary Evaluation of Alternative Liquid Desiccants for a Hybrid Desiccant Air Conditioner, (1988). https://oaktrust.library.tamu.edu/handle/1969.1/6528 (accessed August 31, 2021).
[87] Kinsara AA, Elsayed MM, Al-Rabghi OM. Proposed energy-efficient air-conditioning system using liquid desiccant. Appl Therm Eng 1996;16(10):791–806. https://doi.org/10.1016/1359-4311(95)00090-9.
[88] Dai YJ, Wang RZ, Zhang HF, Yu JD. Use of liquid desiccant cooling to improve the performance of vapor compression air conditioning. Appl Therm Eng 2001;21. https://doi.org/10.1016/S1359-4311(01)00002-3.
[89] Li Z, Liu X, Jiang Y, Chen X. New type of fresh air processor with liquid desiccant total heat recovery. Energy Build 2005;37. https://doi.org/10.1016/j.enbuild.2004.09.017.
[90] Khalil A. An experimental study on multi-purpose desiccant integrated vapor-compression air-conditioning system. JES. J Eng Sci 2010;38(1):105–18. https://doi.org/10.21608/jesaun.2010.123785.
[91] Yamaguchi S, Jeong J, Saito K, Miyauchi H, Harada M. Hybrid liquid desiccant air-conditioning system: experiments and simulations. Appl Therm Eng 2011;31(17-18):3741–7. https://doi.org/10.1016/J.APPLTHERMALENG.2011.04.009.
[92] Zhao K, Liu X-H, Zhang T, Jiang Yi. Performance of temperature and humidity independent control air-conditioning system in an office building. Energy Build 2011;43(8):1895–903. https://doi.org/10.1016/J.ENBUILD.2011.03.041.
[93] Bergero S, Chiari A. Performance analysis of a liquid desiccant and membrane contactor hybrid air-conditioning system. Energy Build 2010;42(11):1976–86. https://doi.org/10.1016/J.ENBUILD.2010.06.003.
[94] Bergero S, Chiari A. On the performances of a hybrid air-conditioning system in different climatic conditions. Energy. 2011;36(8):5261–73. https://doi.org/10.1016/J.ENERGY.2011.06.030.
[95] Zhang L, Hihara E, Saikawa M. Combination of air-source heat pumps with liquid desiccant dehumidification of air. Energy Convers Manage 2012;57:107–16. https://doi.org/10.1016/J.ENCONMAN.2011.12.023.
[96] Zhang Li, Dang C, Hihara E. Performance analysis of a no-frost hybrid air conditioning system with integrated liquid desiccant dehumidification. Int J Refrig 2010;33(1):116–24. https://doi.org/10.1016/J.IJREFRIG.2009.08.007.
[97] Niu X, Xiao F, Ma Z. Investigation on capacity matching in liquid desiccant and heat pump hybrid air-conditioning systems. Int J Refrig 2012;35. https://doi.org/10.1016/j.ijrefrig.2011.08.004.
[98] Xie Y, Zhang T, Liu X. Performance investigation of a counter-flow heat pump driven liquid desiccant dehumidification system. Energy. 2016;115:446–57. https://doi.org/10.1016/J.ENERGY.2016.09.037.
[99] Liu J, Zhang T, Liu X. Model-based investigation of a heat pump driven, internally cooled liquid desiccant dehumidification system. Build Environ 2018;143:431–42. https://doi.org/10.1016/J.BUILDENV.2018.07.027.
[100] Guan B, Liu X, Zhang T, Liu J. Optimal flow type in internally-cooled liquid-desiccant system driven by heat pump: component level vs. system level. Appl

Thermal Eng 2021;183:116208. https://doi.org/10.1016/J.APPLTHERMALENG.2020.116208.
[101] He H, Wang L, Yuan J, Wang Z, Fu W, Liang K. Performance evaluation of solar absorption-compression cascade refrigeration system with an integrated air-cooled compression cycle. Energy Convers Manage 2019;201:112153. https://doi.org/10.1016/J.ENCONMAN.2019.112153.
[102] Mansuriya K, Raja BD, Patel VK. Experimental assessment of a small scale hybrid liquid desiccant dehumidification incorporated vapor compression refrigeration system: an energy saving approach. Appl Therm Eng 2020;174:115288. https://doi.org/10.1016/J.APPLTHERMALENG.2020.115288.
[103] Mansuriya K, Patel VK, Raja BD, Mudgal A. Assessment of liquid desiccant dehumidification aided vapor-compression refrigeration system based on thermo-economic approach. Appl Therm Eng 2020;164:114542. https://doi.org/10.1016/J.APPLTHERMALENG.2019.114542.
[104] Guan B, Liu X, Zhang Q, Zhang T. Performance of a temperature and humidity independent control air-conditioning system based on liquid desiccant for industrial environments. Energy Build 2020;214. https://doi.org/10.1016/j.enbuild.2020.109869.
[105] Lee JH, Jeong JW. Hybrid heat-pump-driven liquid-desiccant system: experimental performance analysis for residential air-conditioning applications. Appl Therm Eng 2021;195:117236. https://doi.org/10.1016/J.APPLTHERMALENG.2021.117236.
[106] ANSI/ASHRAE/IES Standard 90.1-2019 – Energy Standard for Buildings Except Low-Rise Residential Buildings, n.d.
[107] Song M, Wang L, Yuan J, Wang Z, Li X, Liang K. Proposal and parametric study of solar absorption/dual compression hybrid refrigeration system for temperature and humidity independent control application. Energy Convers Manage 2020;220. https://doi.org/10.1016/j.enconman.2020.113107.
[108] Gurubalan A, Maiya MP, Tiwari S. Experiments on a novel membrane-based liquid desiccant dehumidifier for hybrid air conditioner. Int J Refrig 2019;108. https://doi.org/10.1016/j.ijrefrig.2019.09.004.
[109] Bukshaisha AA, Fronk BM. Simulation of membrane heat pump system performance for space cooling. Int J Refrig 2019;99:371–81. https://doi.org/10.1016/J.IJREFRIG.2018.12.010.
[110] Cheon SY, Cho HJ, Jeong JW. Energy saving potential of a vacuum-based membrane dehumidifier in a dedicated outdoor air system. Energy Convers Manage 2021;227:113618. https://doi.org/10.1016/J.ENCONMAN.2020.113618.
[111] Miyazaki T, Akisawa A, Saha BB. The performance analysis of a novel dual evaporator type three-bed adsorption chiller. Int J Refrig 2010;33(2):276–85. https://doi.org/10.1016/J.IJREFRIG.2009.10.005.
[112] Su W, Zhang X. Thermodynamic analysis of a compression-absorption refrigeration air-conditioning system coupled with liquid desiccant dehumidification. Appl Therm Eng 2017;115:575–85. https://doi.org/10.1016/J.APPLTHERMALENG.2016.12.071.
[113] Habib MF, Ali M, Sheikh NA, Badar AW, Mehmood S. Building thermal load management through integration of solar assisted absorption and desiccant air conditioning systems: a model-based simulation-optimization approach. J Build Eng 2020;30:101279. https://doi.org/10.1016/J.JOBE.2020.101279.
[114] Collier R, Arnold F, Barlow R, An Overview of Open-Cycle Desiccant Cooling Systems and Materials, 1981.
[115] Waugaman DG, Kini A, Kettleborough CF. A review of desiccant cooling systems. J Energy Res Technol 1993;115:1–8. https://doi.org/10.1115/1.2905965.
[116] T.R. Penney Ian McClain, Promising Advances in Desiccant Cooling, 1985.
[117] Yong L, Sumathy K, Dai YJ, Zhong JH, Wang RZ. Experimental study on a hybrid desiccant dehumidification and air conditioning system. J. Solar Energy Eng, Trans ASME. 2006;128:77–82. https://doi.org/10.1115/1.2148977.
[118] Chen Z, Zhu J, Bai H, Yan Y, Zhang L. Experimental study of a membrane-based dehumidification cooling system. Appl Therm Eng 2017;115:1315–21. https://doi.org/10.1016/J.APPLTHERMALENG.2016.10.153.
[119] Chung JD, Lee D-Y. Contributions of system components and operating conditions to the performance of desiccant cooling systems. Int J Refrig 2011;34(4):922–7. https://doi.org/10.1016/J.IJREFRIG.2011.03.003.
[120] Caliskan H, Lee DY, Hong H. Enhanced thermodynamic assessments of the novel desiccant air cooling system for sustainable energy future. J Cleaner Prod 2019;211:213–21. https://doi.org/10.1016/J.JCLEPRO.2018.11.174.
[121] Sphaier LA, Nóbrega CEL. Parametric analysis of components effectiveness on desiccant cooling system performance. Energy. 2012;38(1):157–66. https://doi.org/10.1016/J.ENERGY.2011.12.019.
[122] Worek WM, Khinkis M, Kalensky D, Maisotsenko V. Integrated Desiccant–Indirect Evaporative Cooling System Utilizing the Maisotsenko Cycle. In: Volume 1: Heat Transfer in Energy Systems; Theory and Fundamental Research; Aerospace Heat Transfer; Gas Turbine Heat Transfer; Transport Phenomena in Materials Processing and Manufacturing; Heat And, ASME; 2012. https://doi.org/10.1115/HT2012-58039.
[123] Pandelidis D, Anisimov S, Worek WM, Drąg P. Numerical analysis of a desiccant system with cross-flow Maisotsenko cycle heat and mass exchanger. Energy Build 2016;123:136–50. https://doi.org/10.1016/J.ENBUILD.2016.04.039.
[124] Narayanan R, Halawa E, Jain S. Dehumidification potential of a solid desiccant based evaporative cooling system with an enthalpy exchanger operating in subtropical and tropical climates. Energies 2019;12:2704. https://doi.org/10.3390/EN12142704.
[125] Delfani S, Karami M. Transient simulation of solar desiccant/M-Cycle cooling systems in three different climatic conditions. J Build Eng 2020;29:101152. https://doi.org/10.1016/J.JOBE.2019.101152.
[126] Lee Y, Park S, Kang S. Performance analysis of a solid desiccant cooling system for a residential air conditioning system. Appl Therm Eng 2021;182:116091. https://doi.org/10.1016/J.APPLTHERMALENG.2020.116091.
[127] Li H, Dai YJ, Li Y, La D, Wang RZ. Experimental investigation on a one-rotor two-stage desiccant cooling/heating system driven by solar air collectors. Appl Therm Eng 2011;31(17-18):3677–83.
[128] Zeng DQ, Li H, Dai YJ, Xie AX. Numerical analysis and optimization of a solar hybrid one-rotor two-stage desiccant cooling and heating system. Appl Therm Eng 2014;73(1):474–83.
[129] Saghafifar M, Gadalla M. Performance assessment of integrated PV/T and solid desiccant air-conditioning systems for cooling buildings using Maisotsenko cooling cycle. Sol Energy 2016;127:79–95. https://doi.org/10.1016/J.SOLENER.2015.12.048.
[130] Qadar Chaudhary G, Ali M, Sheikh NA, Gilani SIuH, Khushnood S. Integration of solar assisted solid desiccant cooling system with efficient evaporative cooling technique for separate load handling. Appl Therm Eng 2018;140:696–706. https://doi.org/10.1016/j.applthermaleng.2018.05.081.
[131] Heidari A, Roshandel R, Vakiloroaya V. An innovative solar assisted desiccant-based evaporative cooling system for co-production of water and cooling in hot and humid climates. Energy Convers Manage 2019;185:396–409. https://doi.org/10.1016/J.ENCONMAN.2019.02.015.
[132] Farooq AS, Badar AW, Sajid MB, Fatima M, Zahra A, Siddiqui MS. Dynamic simulation and parametric analysis of solar assisted desiccant cooling system with three configuration schemes. Sol Energy 2020;197:22–37. https://doi.org/10.1016/J.SOLENER.2019.12.076.
[133] Song J, Sobhani B. Energy and exergy performance of an integrated desiccant cooling system with photovoltaic/thermal using phase change material and maisotsenko cooler. J Storage Mater 2020;32:101698. https://doi.org/10.1016/J.EST.2020.101698.
[134] Saedpanah E, Pasdarshahri H. Performance assessment of hybrid desiccant air conditioning systems: a dynamic approach towards achieving optimum 3E solution across the lifespan. Energy. 2021;234:121151. https://doi.org/10.1016/J.ENERGY.2021.121151.
[135] Rayegan S, Motaghian S, Heidarinejad G, Pasdarshahri H, Ahmadi P, Rosen MA. Dynamic simulation and multi-objective optimization of a solar-assisted desiccant cooling system integrated with ground source renewable energy. Appl Therm Eng 2020;173:115210. https://doi.org/10.1016/J.APPLTHERMALENG.2020.115210.
[136] Kousar R, Ali M, Sheikh NA, Gilani SIuH, Khushnood S. Holistic integration of multi-stage dew point counter flow indirect evaporative cooler with the solar-assisted desiccant cooling system: a techno-economic evaluation. Energy Sustain Dev 2021;62:163–74. https://doi.org/10.1016/J.ESD.2021.04.005.
[137] Zhou X. Thermal and energy performance of a solar-driven desiccant cooling system using an internally cooled desiccant wheel in various climate conditions. Appl Therm Eng 2021;185:116077. https://doi.org/10.1016/J.APPLTHERMALENG.2020.116077.
[138] El-Dessouky HT, Ettouney HM, Bouhamra W. A novel air conditioning system: membrane air drying and evaporative cooling. Chem Eng Res Des 2000;78:999–1009. https://doi.org/10.1205/026387600528111.
[139] Lin J, Thuan Bui D, Wang R, Chua KJ. Investigation of dew point evaporative cooling with vacuum membrane dehumidification. Energy Procedia 2017;142:3851–6. https://doi.org/10.1016/J.EGYPRO.2017.12.287.
[140] Chun L, Gong G, Peng P, Wan Y, Chua KJ, Fang X, et al. Research on thermodynamic performance of a novel building cooling system integrating dew point evaporative cooling, air-carrying energy radiant air conditioning and vacuum membrane-based dehumidification (DAV-cooling system). Energy Convers Manage 2021;245:114551. https://doi.org/10.1016/J.ENCONMAN.2021.114551.
[141] U.S. Energy Information Administration, Form EIA-860 Annual Electric Generator Report, 2019. https://www.eia.gov/electricity/data/eia860/.