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Separate Sensible and Latent Cooling Systems: A Critical Review of the State-of-the-Art and Future Prospects

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ABSTRACT

Dehumidification is a major contributor to the energy consumed by residential and commercial buildings. Emerging separate sensible and latent cooling (SSLC) systems can provide energy-efficient solutions to control moisture and temperature independently. In light of emerging research, a strong need has emerged to categorize and to characterize the performance of SSLC systems. The current study provides categorization and a critical review of major developments, including components, systems, processes and working media pertaining to SSLC systems. The review highlights the key features which can be used for classification, performance evaluation and steady-state capacity of SSLC systems. Finally, the study provides guidelines for further research and important performance matrixes for future developments.

1. INTRODUCTION

Control of the water vapor content in air is necessary to maintain desired indoor conditions in buildings and certain industrial processes. Restaurants, indoor swimming pools or spas are examples of premises with high latent loads. Up to 80% of a person's time is now spent indoors in a closed environment. At present, the role of providing thermal comfort and indoor air quality is primarily fulfilled by mechanical heating, ventilation and air conditioning (HVAC) systems. Whilst today's mechanical HVAC systems are capable of delivering the necessary conditions to occupants of comfortable indoor conditions, HVAC systems account up to 40% of the total energy consumption of buildings.

The relative humidity of supply air can have a significant impact on the energy consumption of HVAC systems. High relative humidity levels coupled with moderate-to-high air temperature leads to discomfort to occupants. By reducing the level of relative humidity in the air, occupant comfort would increase. High moisture content of indoor air can also have serious health implications for occupants. The presence of high moisture content and warm indoor air temperatures can result in the growth of bacteria and mold that can affect occupant health. More precise control of the relative humidity of indoor air prevents bacteria and mold build-up.

For human thermal comfort, three modes of heat transfer are relevant: evaporation, convection, and radiation. In other words, the important features of a conditioned space are the air temperature, air humidity, and mean radiation balance. HVAC systems must be designed to provide thermal comfort by providing conditions that will result in a comfortable balance of radiant, convective, and evaporative heat transfer to/from the inhabitants.

2. SSLC vs. CONVENTIONAL COOLING SYSTEMS

An SSLC system is defined as one in which all or most of the latent cooling is provided by one device, and all or most of the sensible cooling is provided by another device. The two devices may be part of the same thermodynamic cycle (for example a single VCS compressor operating with two evaporators at different temperature/pressure levels). In theory, the two devices might even occupy the same physical space. Examples of this are a membrane dehumidifier integrated onto the surface of a VCS evaporator; or liquid desiccant droplets being pre-cooled to the extent that they sensibly cool the air in contact with them, in addition to removing moisture. The important distinguishing feature of an SSLC system is the design intent to deliver humidity and temperature control separately. Importantly, a vapor compression system aiming for sensible-only cooling can have a higher COP than the one in the TC device, since it need not cool below the air dewpoint.

A conventional air-conditioning system manages two kinds of cooling loads, the sensible and latent loads. The sensible cooling is achieved by an evaporator by reducing the temperature of the supply air. During conventional operation the refrigerant temperature in the evaporator is below the dew point of the supply air, and moisture in the air condenses on the evaporator to reduce the humidity ratio of the delivered air. Thus, latent heat is removed due to the condensation of water vapor in the air.

Theoretically, the process of supply air flowing through the evaporator follows the path that is composed of a horizontal sensible load removal part (point A to point B) and a latent load removal part along the 100% relative humidity (RH) line from B to C, as presented in Fig. 1. Commonly, the temperature of point C is too low for thermal comfort, therefore a reheat process is sometimes performed by which temperature is increased from point C to the temperature of point D. The reheat process, usually carried out by electric heaters, requires extra energy input and increases the total net energy input. Hence, the reheat process reduces the overall performance of the system.

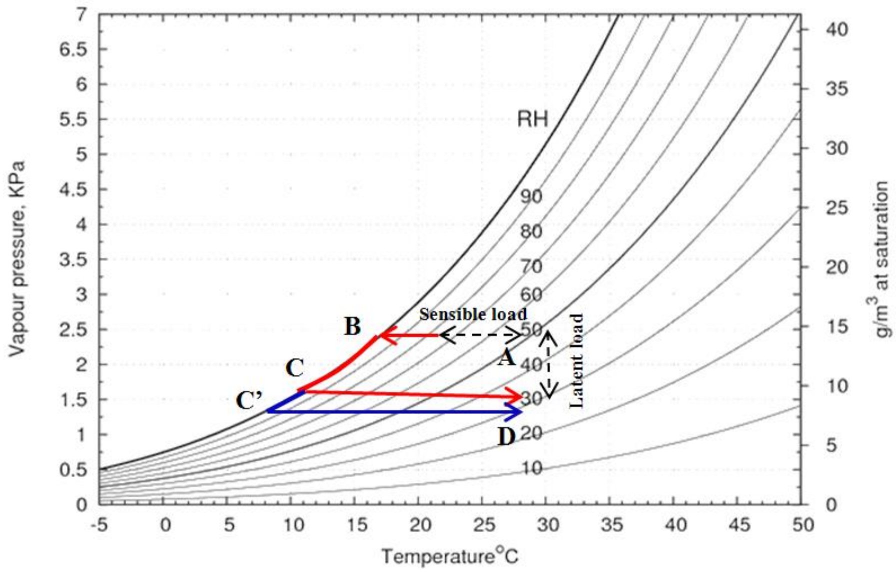


Figure 1: Operation of conventional air conditioning system (Nawaz *et al.*, 2014a, 2014b)

Separate sensible and latent cooling (SSLC) systems are considered a possible alternative to conventional air conditioning systems. The psychrometric process of a SSLC system is presented in Fig. 2. This system consists of one vapor compression system and one liquid/ solid desiccant system. The vapor compression system provides only sensible cooling (point A to point B) required by the conditioned space at both elevated air temperature leaving the evaporator and a higher air mass flow rate. The reason for a higher air mass flow rate requirement is to compensate for the reduced enthalpy difference of air across the evaporator, and to maintain the capacity of sensible cooling. Since the vapor compression system operates above the dew point temperature of supply air and is not required to provide the latent cooling, the desiccant (solid/liquid) system is used to reduce the water vapor content in the part of the air leaving from the sensible evaporator. The part of the dry air from the desiccant wheel mixes with the rest of the air from the evaporator and is delivered to the conditioned space (point D).

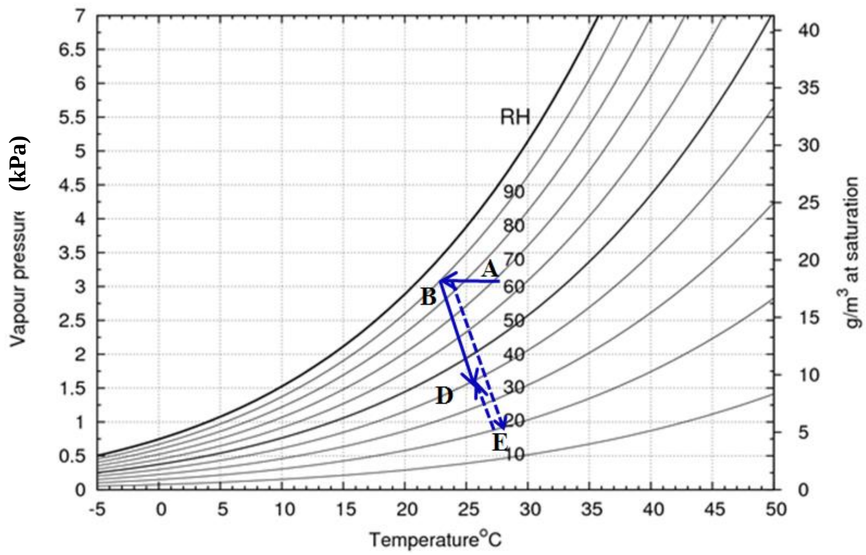


Figure 2: Operation of SSLC system (with enthalpy wheel)

To summarize, SSLC systems have two features which distinguish them from the conventional systems. First, since the vapor compression system used in an SSLC system operates above the dew point temperature, the supply air temperature is thermally comfortable and can be sent to the conditioned room directly. Hence, no reheat is necessary in SSLC systems. Secondly, an SSLC system uses a vapor compression system to provide sensible cooling. As a consequence, any fluctuations in sensible cooling demand can be simply met by changing the capacity of the vapor compression system. In order to meet the fluctuations of latent cooling demand, the capacity of the desiccant system can be enhanced, for example the rotation speed of the enthalpy wheel can be adjusted or the flow rate of the liquid desiccant can be increased to provide the latent cooling load. However, it should be noticed that the loads are still coupled due to the mixing of streams, and such processes can be performed within a limited range of operation. Any latent cooling demand change beyond the reach of the potential adjustment in solid/liquid desiccant system will be unmet. Such drawbacks justify the need of desiccant moisture removal device with more independent load matching and better operation control. Furthermore, although a desiccant based system is a stand-alone device providing latent cooling, any amount of the latent capacity change would theoretically lead to the same amount of change in sensible heat generation. Therefore, the vapor compression system must increase the cooling capacity to cover the extra heat. Thus, there is still a link between the processes in vapor compression system and desiccant wheel and the independent treatment is sometimes leads to impractical conclusions.

The combination of a latent-only desiccant wheel with a VCS cooling cycle has been called "hybrid (desiccant) cooling" by some authors (Fong *et al.*, 2011, Khalid *et al.*, 2009, Dong *et al.*, 2011, Mohammad *et al.*, 2013, Heidarinejad and Pasdarshahri, 2011, Enteria *et al.*, 2012, Nawaz *et al.*, 2015). The term SSLC has been used in (Ling *et al.*, 2011). Although less widely used so far, the term SSLC is preferred since it is simultaneously more specific to systems that treat latent and sensible loads separately, and more descriptive of the diverse range of systems that fall under this classification. In addition, systems that provide both latent and sensible cooling by two distinct VCS evaporators by Ling *et al.*, (2010).

One note has to be made here: the SSLC technology can be applied to systems other than VCS such as absorption system and adsorption system. Gluesenkamp *et al.* (2011) proposed the modeling of an absorption cycle which operated at a high evaporating temperature of 35°C providing sensible cooling only. The latent cooling in the model was fulfilled by a downsized VCS, as shown in Fig. 3. The SSLC technology applied to the absorption system solved the issue of crystallization of LiBr solution by elevating the evaporating pressure. Hence the rich solution path was pushed up and farther away from the crystallization line (Fig. 4).

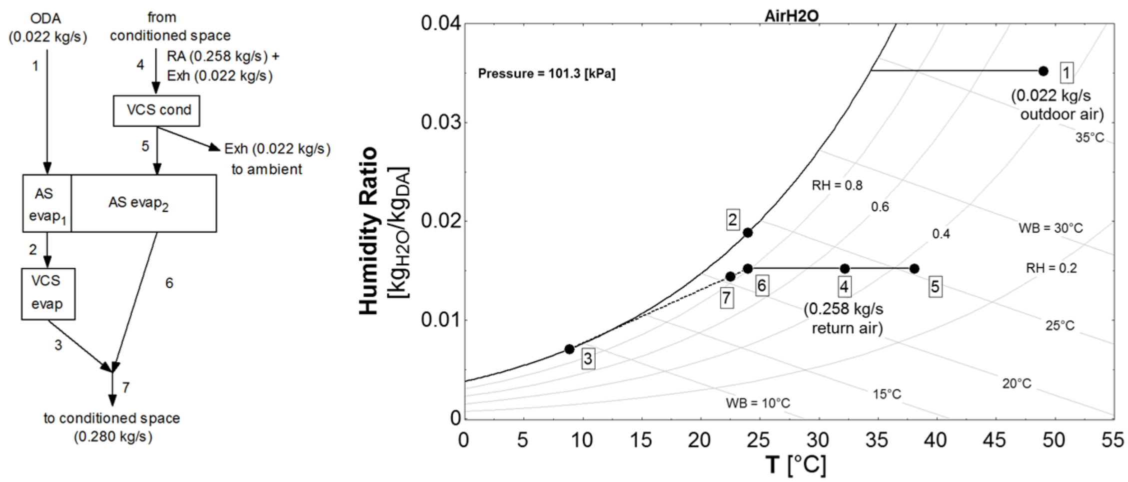


Figure 3: Air flow schematic (left) and Psychrometric chart (right) of the SSLC absorption system with a supplementary VCS

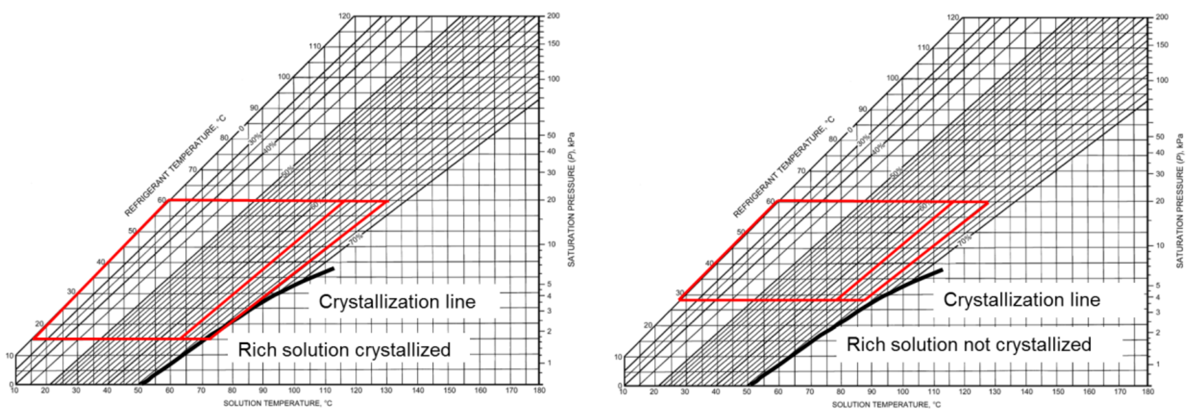


Figure 4: Effect of crystallization mitigation by applying the SSLC technology

3. CLASSIFICATION OF SSLC SYSTEMS

3.1 Classification by Device Type

By “device type” in this work, it is meant the type of cooling provided by a device. A cooling device can act on the air in the space, or it can affect the radiation balance experienced by the occupants. The classification here is based on what is most directly affected by the device: secondary effects are not used (an example of a secondary effect is cooler radiative surfaces as a byproduct of cooling the air). The three device types are described below.

- **Total cooling (TC) devices:** One way a device can act directly on the air is to lower the air temperature. If the outlet air from the device is lower than the inlet air’s dew point, the device provides both sensible and latent cooling. Thus, these devices are TC devices.
- **Latent only (LO) devices**: It is also possible to act directly on the humidity content of the air, which may result in an incidental increase in dry bulb temperature. A desiccant wheel provides latent cooling while typically increasing the temperature of the process air. A VCS can be configured such that process air passes first over the evaporator and then the condenser before being supplied to a space. These devices are LO devices. On the other hand, a liquid desiccant device can provide both sensible and latent cooling, i.e., a TC device, since the salt solution can be precooled.
- **Sensible only (SO) devices**: Finally, a device can lower the dry bulb temperature of air without affecting the moisture content. A TC device operating above the dewpoint acts as a SO device. A dedicated SO device is one that is not capable of, or is not designed for, total cooling. This could be a vapor compression system without provision for condensate removal at the evaporator, for example. It is also important to consider

radiant cooling devices, such as chilled ceiling panels or chilled beams. A radiant device affects thermal comfort by affecting the mean radiation temperature felt by a person, without necessarily affecting air temperature. An example would be an overhead outdoor propane heater – even if a natural convection or a breeze prevent any sensibly heated air from reaching a person below, the person is warmed by the direct infrared radiation. Thus, although they do not necessarily act on the air at all, radiant devices should be included as SO devices. And in fact, even when affecting the air temperature, a radiant cooling device will typically be intentionally designed to avoid latent cooling, since condensation in indoor environments is undesirable.

The three types just introduced are intuitive, but problematic. Consider that, although the above classification treats sensible, latent, and radiant cooling independently, as three possible axes of action. However, it is easy to imagine and to construct devices that combine these effects: a total cooling device can operate above the dewpoint (TC_{ADP}), in which case it behaves as a SO device, or below the dewpoint (TC_{BDP}). In addition, a LO device can increase dry bulb, or have no effect; likewise, an SO can increase or have no effect on absolute humidity.

To resolve these ambiguities, Table 1 is used to classify cooling devices into 5 types, designated Type I – Type V. Note that that Table 1 contains 9 combinations. Three of these are heating devices and one is neither a heating nor a cooling device; the remaining 5 are assigned to three cooling device types (TC, LO, and SO).

Table 1 does not preclude the possibility of a device that increases the specific enthalpy of the process air, either by sensibly heating more than it sensibly cools or vice versa. In other words, Type III and Type V in Table 1 each has subtypes of decreasing, neutral, and increasing specific enthalpy. This distinction is not merely academic, as real desiccant wheels commonly increase process air specific enthalpy, and direct evaporative coolers do not change the process air enthalpy; yet both can be useful, especially in SSLC systems.

Table 1: Definitions of device types

		Effect on dry bulb temperature		
		Decrease	**No change**	**Increase**
Effect on absolute humidity	**Decrease**	Type I *TC_{BDP}*	Type IV *LO*	Type V *LO*
	No change	Type II *SO*, *TC_{ADP}*	(Not a heating or cooling device)	(Heating device)
	Increase	Type III *SO*	(Heating device)	(Heating device)

Table 1 is represented graphically as an enthalpy wheel in Fig. 6. Here, Q is defined as positive when cooling is provided, and negative when heating is provided. Examples of components for each category are:

- Type I: chilled coil operating below the dewpoint (TC_{BDP})
- Type II: chilled coil operating above the dewpoint (TC_{ADP}); radiant cooling device; indirect evaporative cooler
- Type III: direct evaporative cooler
- Type IV: chilled liquid desiccant waterfall (operating such that it has neutral effect on dry bulb temperature of process air); isothermal membrane-based dehumidifier
- Type V: desiccant wheel; adiabatic liquid desiccant waterfall, membrane-based dehumidifier operating above the process air dry bulb temperature

Fig. 5 clearly shows the three subtypes of Type III and V, depending on the total enthalpy effect (decrenthalpic, isenthalpic, or augmenthapic). It also shows the saturation lines for Type I devices. These saturation lines approaches 0 as $T\to\infty$, and approaches 1 as $T\to 0$ K. For clarity, Fig. 6 does not include SO devices that increase absolute humidity ($Q_L<0$), such as direct evaporative coolers.

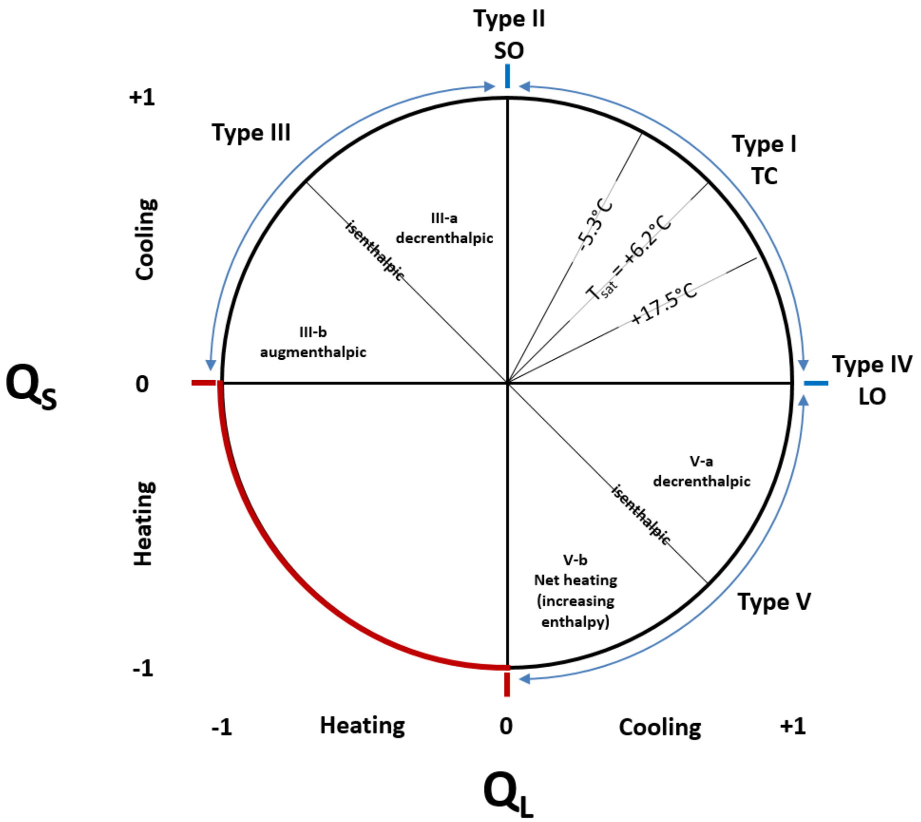


Figure 5: Definition of device types

Since latent and sensible cooling are provided separately in an SSLC system, Table 2 characterizes all combinations of devices that can make up an SSLC system, under the three assumptions that (1) both sensible and latent cooling are provided, (2) at most one device is used for latent cooling, and (3) at most one device for sensible cooling. Tables 1 and 2 would not change with technological advances.

Table 2: Classification of SSLC systems into 9 combinations of device type

		Sensible load met by:		
		I	IV	V
Latent load met by:	I	I/I	IV/I	V/I
	II	I/II	IV/II	V/II
	III	I/III	IV/III	V/III

Note that for V/III systems, at least one device must be capable of reducing the specific enthalpy of process air (for example, a direct evaporative cooler with an isenthalpic desiccant wheel is precluded since it would not be capable of providing total cooling).

Thus, assuming no more than two devices per system, there are nine possible SSLC systems (or pairwise device type combinations) that can be used to form an SSLC system. Only a few have been explored in the literature. Ling *et al.* (2010) have investigated the TC/TC type and extended the work to include the potential enhancement options for such systems (Ling *et al.*, 2013). Most hybrid (desiccant) systems utilize the TC/LO type. The combination of SO/TC can only save energy when heat recovery devices are utilized in the entire system. The idea of SO/LO is an attractive combination in that it provides truly independent controls, potentially providing better thermal comfort.

3.2. Classification by Cycle Type

The *device type* is an abstract classification based on the function provided, and the *cycle type* is the actual hardware employed.

By definition, sensible and latent cooling are provided separately in SSLC systems. Therefore, it is possible to classify SSLC systems by what type of *cycle* provides each type of cooling. This classification is dependent on the cycle types (hardware technology) that become technologically feasible and available, and is independent of, and in addition to, the classification by device type in Table 1. In the present work, the cycles listed in Table 3 for each device type are considered.

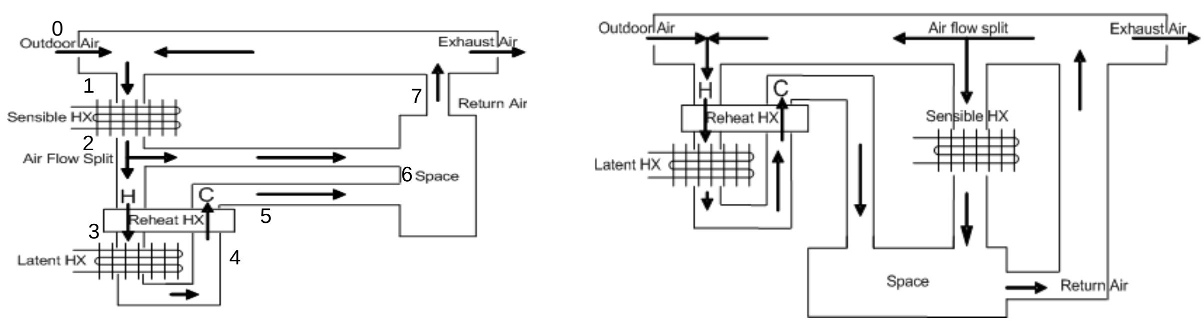
Table 3: Cycle types considered in this work

Device type		Cycles considered
Total cooling (TC)		VCS, HATCD, TE, IEC
Latent-only cooling (LO)		DW, MD, VCS-SEC
Sensible-only cooling (SO)	RC	RC-TC_{ABD}
	Via air	DEC, TC_{ADP}

For the thermally-driven cycles (HATCD and DW), a further distinction must be made with regard to the driving heat source. HATCD can be directly driven by combustion of fuel (DF) or by waste heat (WH). The temperature level of WH varies significantly among different systems. WH of 100°C or more can be used to drive adsorption/absorption system and, of course, DW. Traditionally, WH less than 50°C has no practical usage since it is not hot enough to drive any abovementioned systems. Fortunately, the current research in desiccant material has successfully reduced the requirement of regeneration temperature from previously at least of 80°C down to around 45°C. This allows the integration of VCS and DW without the usage of auxiliary heater which is traditionally required to increase the temperature of air after the condenser before entering the DW. Table 4 illustrates possible permutations. For clarity it only considers two TC devices (VCS and HATCD), two LO devices (DW and VCS-SEC), and two SO devices (RC and DEC). Also for clarity it does not specify the cycle used in the case of RC. As additional cycles are included as possibilities in Table 4, the number of permutations increases rapidly.

3.3. Classification by Air Flow Configuration

The air flow configurations of different SSLC systems are numerous, and generally speaking, they are more complicated than those of conventional systems. Fig. 6 show two kinds of airflow configurations of two SSLC systems which use two independent vapor compression systems. In the serial configuration, the return air flow is first mixed with outdoor air before flowing to the sensible evaporator. The airflow after the sensible evaporator is divided into two parts: one of the flows enters the space as part of the supply air; the other stream enters a reheat HX to be pre-conditioned by using the cooling from the latent HX and then flows through the latent HX before entering the space. In the parallel configuration, part of the return air flows through the sensible HX before mixing with the outdoor air. The mixed air stream then flows through the reheat HX and the latent HX in sequence. Both the air flow configurations are complicated which requires multiple dampers or fans to direct the flows. Figure X shows an experimental setup from Ling *et al.* (2011). The test setup was used to carry out experimental tests of SSLC system using VCS and DW. In this setup, multiple electronic dampers were used to flow through or bypass the desiccant wheel. The complicated air flow configuration requires a careful design of system layout as well as the sizing of fans or blowers. Extra pressure lift should be considered for fan design due to the application of the dampers.



a) Serial configuration b) Parallel configuration

Figure 6: Air flow configurations of SSLC systems using two VCCs

4. FUTURE PERSPECTIVE

Regardless of extensive developments, the implementation of SSLC is still a challenge and will require further research and development efforts for commercialization of such systems. Some key areas of future research include:

1- Development of new heat and mass exchanger: Heat and mass exchangers are critical part of SSLC system and the capital and operational cost depends on the characteristics of these devices.
2- Development and evaluation of desiccants (liquid and solid): Such development is critical to establish both steady state and transient properties of such systems. Along with the cost the operational sustainability and durability is also heavily dependent on working medium.
3- Regeneration processes: One major challenge for the existing technologies is to incorporate appropriate regeneration processes. Currently, various options such as solar, condenser heat, and industrial waste heat have been considered, however, with the development of new SSLC systems requiring specific operating conditions; such processes have limited implications. Thus, there will be strong need to develop processes which can effectively regenerate the working substance
4- Retrofitting opportunities and challenges: With the increasingly critical requirement for limited footprints of HVAC&R systems, it is very important to develop compact system which can be easily retrofitted in to existing infrastructures.

5. CONCLUSIONS

The article provides an overview of the existing SSLC technologies. Such systems have clear benefits compared to the conventional single vapor compression systems by eliminating the energy intensive processes (i.e., additional cooling and heating). However, there has been extensive development in this fields and this requires an overview of the technology to classify various systems. While there are multiple criteria which can be used however, classification based on device type, cycle configuration and air flow configuration have been discussed and the associated features have been highlighted. Based on existing development some prospective for the future development have been discussed which will be subjects of interest for further research and development efforts in SSLC systems.

ACRONYMS

SSLC	Separate Sensible and Latent Cooling	COP	Coefficient of Performance
HVAC	Heating, Ventilation and Air- Conditioning	RH	Relative Humidity
TC	Total Cooling	ADP	Above Dew Point
LO	Latent Only	BDP	Below Dew Point
SO	Sensible Only	HATCD	Heat Assisted Thermal Cooling and Dehumidification
VCS	Vapor Compression System	TE	Thermo Electric
RC	Radiant Cooling	DEC	Direct Evaporative Cooling
MD	Membrane based Dehumidification	DW	Desiccant Wheel

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