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ABSTRACT

A liquid-desiccant (LD) air dehumidification removes moisture in the air through an absorption process. It does not need to cool the process air down to the dew point temperature as in conventional vapor compression refrigeration (VCR) systems. The LD dehumidification (LDD) system can be combined with a sensible cooling system to control the temperature and humidity of an indoor environment independently. The LDD system requires heating for regenerating the diluted LD (i.e., removing the absorbed water vapor from the LD). Earlier LD dehumidification systems require a high concentration of LD for dehumidification and a high-temperature heat source for regeneration, commonly above 60°C. Electric resistance heaters or combustion-based regenerators were used to reach the required regeneration temperatures. An alternative approach has emerged in recent years, which uses a heat pump to provide both the cooling and heating needed for dehumidification and regeneration. Thus, the heat-pump-driven LDD (abbreviated as HP-LDD) can operate the dehumidification and regeneration at a lower temperature and concentrations than the conventional LDD system without any additional heat resources, resulting in higher system efficiency than the conventional dehumidification systems using VCR.

The paper reviews the working principle of the HP-LDD systems and the requirements of the dehumidification and regeneration processes. The advantages of the HP-LDD systems over the conventional LDD systems and the VCR-based air-conditioning systems are also discussed. Then, recent studies of the HP-LDD systems are reviewed to provide a comprehensive comparison and in-depth analysis of system configuration, component design, energy efficiency, and dehumidification performance. LD selection, heat pump integration, and needed controls for the HP-LDD systems are also discussed. Finally, an outlook is presented for future research to overcome the identified limitations and improve system performance.

1. INTRODUCTION

Air Conditioning (AC) systems provide sensible and latent cooling to maintain indoor air at comfort temperatures and humidity ratios. Vapor Compression Refrigeration (VCR), the most commonly used AC system, reduces air moisture via condensation by cooling down the air to the dew point temperature of the process air. This process reduces air temperature lower than human thermal comfort level, generating local thermal discomfort when supplied to the building directly (American Society of Heating, 2017). Thus, the conditioned air from the VCR is typically heated to meet occupancy thermal comfort. Due to the overcooling and reheating, VCR-based air dehumidification is not energy efficient. Liquid desiccant-based dehumidification (LDD) is one possible alternative to VCR-based air dehumidification. It uses Liquid Desiccant (LD), which is characterized by a strong affinity for water. LD absorbs the air's moisture and then releases it to another stream to regain the initial concentration for continuous operation. The LD system requires cooling and heating, respectively, to provide adequate water absorption and desorption conditions.

Earlier designs of LD based dehumidification systems use heating power at elevated temperatures to regenerate LD to its initial high concentration (required in the dehumidification process) to ensure dehumidification capacity (Burch et al., 2012; Dean et al., 2012; Kozubal et al., 2011; Kozubal, Herrmann, Deru, & Clark, 2014; Kozubal,

Herrmann, Deru, Clark, et al., 2014; Salikandi et al., 2021). The regeneration temperature ranges between 60 °C and 140 °C and common combustion or electric resistance heating sources are used. The use of solar energy and waste energy sources to mitigate the energy needs for high-temperature regeneration was evaluated (Burch et al., 2012; Dean et al., 2012; Kozubal et al., 2011; Kozubal, Herrmann, Deru, Clark, et al., 2014). Despite experimental work that proved the feasibility of such configurations, the systems were complex and large. These regeneration temperatures generated high sensible loads which need to be provided for by an auxiliary sensible cooling system. To improve the above-mentioned configurations, Heat Pumps (HP) as heating and cooling sources for LDD systems has been studied (Abdel-Salam & Simonson, 2016; Qi et al., 2020). The use of HP for this application is more energy-efficient than the direct use of VCS, because the evaporator temperature does not need to be low enough to generate water condensation. Since the HP evaporator cools the LD before entering the dehumidifier, it is possible to reach the required concentration in the regenerator using only the heat rejected by the HP compressor, which can range between 32 °C and 55 °C (Guan et al., 2020; Lee & Jeong, 2021; Liang et al., 2021; J. Liu et al., 2020; X. Liu et al., 2018; Q. Zhang et al., 2020). This type of design tackles several problems from the previous configuration, such as reducing the number of devices required, simplifying the overall system, and reducing the sensible cooling needs from the auxiliary cooling system.
Several research groups have studied Heat Pump-coupled Liquid Desiccant-based Dehumidification (HP-LDD) systems by experimental and modeling methods. There is a need to review and systematize the findings of different authors for the outlook of LDD technologies. This paper presents a review of HP-LDD systems papers from 2017 onwards. Various system configurations and components are first analyzed, and different systems' dehumidification and energy performance are compared. Finally, challenges for the further development of HP-LDD systems are identified to provide an outlook on the potential directions of future research efforts.

2. WORKING PRINCIPLE OF LIQUID DESICCANT DEHUMIDIFICATION

An LDD system has two mass exchange processes: air dehumidification and LD regeneration. Dehumidification removes water molecules from the process air by the LD solution in the dehumidifier. By absorbing air-water during dehumidification, the concentration of the LD diminishes. As the air temperature increases due to the exothermic nature of the absorption process, the water vapor differential between air and LD reduces, thus impairing the mass transfer and moisture removal. Regeneration removes the absorbed water from the diluted LD to restore LD initial concentration and thus maintain the dehumidification capacity of the system. Regeneration is an endothermic process, and as the fluid temperature diminishes, the vapor pressure differential driving the mass exchange diminishes. The system can maintain its dehumidification capacity by performing these processes in parallel. Cooling and heating sources are required to sustain the dehumidification and regeneration processes. The most basic configuration possible for an LDD system must address the discussed characteristics, e.g., the system must possess dehumidification and regeneration devices, along with heating and cooling sources.

The dehumidifier receives high concentration, low-temperature LD and exposes it to the high humidity process air stream. Process air exits the dehumidifier with lower humidity, while LD leaves at lower conceentration. These parameters are highly variable for different system configurations and operation conditions, and no general rules regarding outlet temperatures can be defined. On the regenerator, hot LD is exposed to outdoor or return scavenging air. The scavenging air leaves at a higher temperature and moisture content, while the LD leaves at a lower temperature and higher concentration, having recovered its initial moisture removal capacity. An LDD system may contain LD recirculation loops and heat recovery heat exchangers, to improve its dehumidification or energy performance. Figure 1a presents a diagram representing a LD-based system that describes the essential devices.

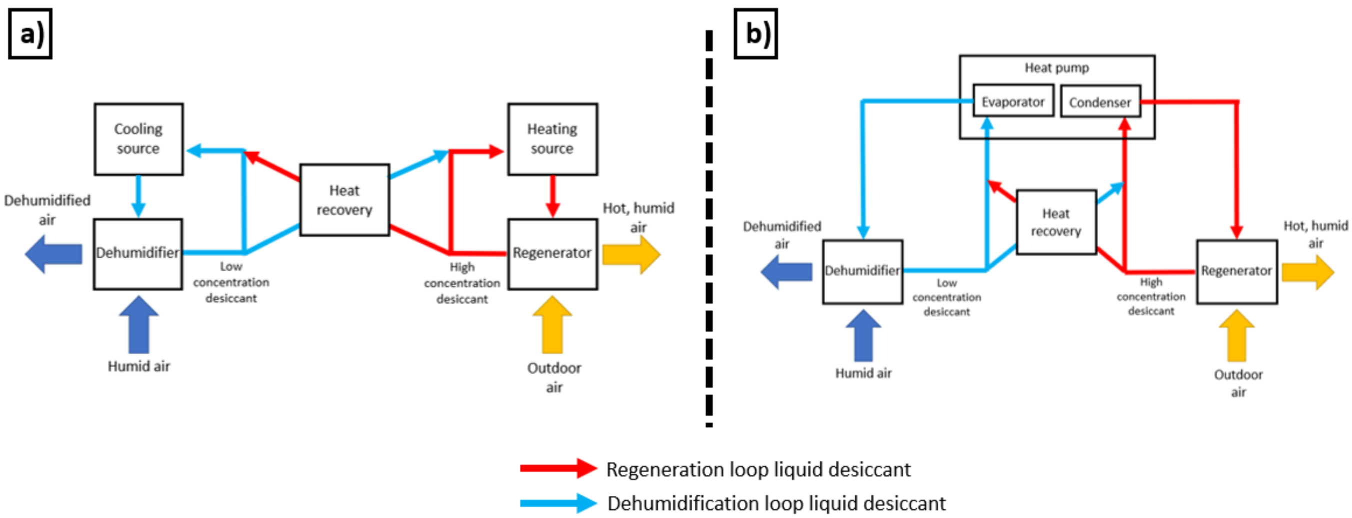

Figure 1: LDD Schematic system diagram

3. HP-LDD systems review

3.1 System configurations

HP-LDD systems show significant agreement regarding the arrangement of the core elements, such as HP and mass exchange devices in the general LDD system, shown in Figure 1b. Most designs present asymmetrical absorption and desorption configuration, considering the same type, arrangements, and number of absorbers and desorbers (Abdel-Salam & Simonson, 2014; Guan et al., 2020, 2021; Lee et al., 2021; Lee & Jeong, 2021; Liang et al., 2021; J. Liu et al., 2018, 2020; X. Liu et al., 2018; Peng & Luo, 2020; N. Zhang et al., 2018; N. Zhang & Yin, 2017; Q. Zhang et al., 2020), even though these processes present different requirements. Most designs include heat recovery between the dehumidification and regeneration LD circuits via sensible heat exchangers (Abdel-Salam & Simonson, 2014; Guan et al., 2021; Liang et al., 2021; J. Liu et al., 2018, 2020; Shan et al., 2018; N. Zhang et al., 2018; N. Zhang & Yin, 2017; Q. Zhang et al., 2020). The common symmetrical core elements design exceptions are due to slightly different applications rather than dehumidification or energy performance optimization (Sanaye & Taheri, 2018; Shan et al., 2018; Su et al., 2018).

3.1.1 System applications: LDD systems must provide sensible and latent cooling to replace VCR. According to the system configurations considered by different authors to provide sensible and latent cooling, HP-LDD systems can be classified into the following three groups.

1. Separate Sensible and Latent Cooling (SSLC) systems: An SSLC system requires additional elements to provide sensible cooling. The additional element, typically, is connected to the evaporator of a VCR system. In general, the systems in the SSLC category use open towers, adiabatic dehumidifiers, and regenerators (Lee et al., 2021; Lee & Jeong, 2021; Sanaye & Taheri, 2018; Su et al., 2018).
2. Total cooling systems: In total cooling systems, the supply air undergoes sensible and latent cooling in the dehumidifier using low-temperature LD or low temperature internal cooling fluid. This configuration differs from VCR total cooling because the air is cooled down only to the required supply temperature, above the dew point of the process air, for human comfort. Total cooling LDD systems can be classified into complete total or partial cooling. Supply air is cooled down to its intended supply temperature inside the complete total cooling systems dehumidifier (X. Liu et al., 2018; Q. Zhang et al., 2020)(Liang et al., 2021). Partial total cooling systems provide sensible cooling in the dehumidifier but require additional sensible cooling before reaching the intended supply temperature. In this category, open tower, internally cooled dehumidifiers can be found (J. Liu et al., 2018, 2020).
3. Dehumidification only systems: No significant sensible cooling provided by the dehumidifier or sensible cooling devices. In this category, different dehumidifier types can be found, such as flat plate membrane (Abdel-Salam & Simonson, 2014), adiabatic open tower (Guan et al., 2020; Peng & Luo, 2020), internally

cooled open tower (Guan et al., 2021) and hollow fiber membrane dehumidifiers (N. Zhang et al., 2018; N. Zhang & Yin, 2017).

3.1.2 Heat transfer fluids: Commonly, hygroscopic salts-based solutions are used as LD. These solutions are corrosive at low temperatures and present crystallization risk when at high concentrations. The most commonly used LD in the works reviewed is Lithium Chloride (Abdel-Salam & Simonson, 2014; Lee et al., 2021; Lee & Jeong, 2021; Peng & Luo, 2020; Shan et al., 2018; N. Zhang et al., 2018; N. Zhang & Yin, 2017), although Lithium Bromide (Guan et al., 2020, 2021; Liang et al., 2021; J. Liu et al., 2018, 2020) and Calcium Chloride (X. Liu et al., 2018; Sanaye & Taheri, 2018) have also been used. Despite these disadvantages, several designs consider the direct use of hygroscopic salts-based LD on their heat exchangers as heat transfer fluid (Guan et al., 2020, 2021; Lee et al., 2021; Lee & Jeong, 2021; Liang et al., 2021; J. Liu et al., 2018, 2020; X. Liu et al., 2018; Peng & Luo, 2020; Sanaye & Taheri, 2018; Shan et al., 2018; Su et al., 2018; N. Zhang et al., 2018; N. Zhang & Yin, 2017; Q. Zhang et al., 2020). However, limited discussion about the component materials required for withstanding corrosive LD operation is presented, with only one case indicating the use of corrosion-resistant titanium heat exchangers (X. Liu et al., 2018). As an alternative to the use of corrosion-resistant devices, water can be used as a heat transfer fluid to avoid corrosion and crystallization risks (Abdel-Salam & Simonson, 2014). Another option is the direct use of refrigerant as heat transfer fluid (Guan et al., 2021; Liang et al., 2021; J. Liu et al., 2018, 2020). In this case, the dehumidifier and regenerator act as both mass exchange devices for the dehumidification system, and evaporator and condenser for the HP.

3.1.3 Heat recovery: A source of energy inefficiency in LDD systems is the need for providing heating and cooling to the same fluid at different points of the circuit. To replace weakened LD after dehumidification, hot, strong LD is diverted to the dehumidification section. At the same time, diluted LD at a lower temperature at the outlet of the dehumidifier needs to be heated and regenerated. A common measure to reduce energy cancellation is to place a heat exchanger at the point at which these two LD streams meet (Abdel-Salam & Simonson, 2014; Guan et al., 2021; Liang et al., 2021; J. Liu et al., 2018, 2020; Shan et al., 2018; N. Zhang et al., 2018; N. Zhang & Yin, 2017; Q. Zhang et al., 2020).

3.2 Heating operation

Besides the use of LDD for latent cooling, some authors have studied the feasibility of using the same system during the heating season (Lee et al., 2021; Lee & Jeong, 2021; Liang et al., 2021; Peng & Luo, 2020; Su et al., 2018). In these cases, the working principle remains the same, but the goal is to use the exhaust air from the regenerator as the supply air to the building. The regenerator exhaust air leaves at higher humidity and temperature, thus making it useful in cold, dry climates during the winter. In this operation mode, it is possible to provide supply air at a humidity ratio between 6.3 [g/kg] and 15.5 [g/kg] and temperatures between 17°C and 37°C. To reach these results, LD must enter the regenerator at temperatures between 32°C and 39.5°C, with a concentration between 30% to 51.7%. This operation mode presents some particular challenges, such as the increased risk of crystallization for operation at low temperatures, additional heating sources for sensible heating or solution heating, and the need to increase the humidity of the solution using tap water to reach the target supply humidity. This promising operation mode can improve the usability of the system year-round, provide comfortable humidity levels to the users and operate at a relatively high Coefficient Of Performance (COP) given by the use of the HP as a heating source.

3.3 Components review

3.3.1 Dehumidifier and regenerator design: The essential devices in LDD systems are the dehumidifier and regenerator. The open tower is the most commonly used type of mass exchanger (Guan et al., 2020, 2021; Lee et al., 2021; Lee & Jeong, 2021; Liang et al., 2021; J. Liu et al., 2018, 2020; X. Liu et al., 2018; Peng & Luo, 2020; Sanaye & Taheri, 2018; Shan et al., 2018; Su et al., 2018; Q. Zhang et al., 2020). Although they have a reliable and straightforward design, they present inconveniences, such as large volumes and LD droplets carryover. Some configurations use membrane-based dehumidifiers and regenerators to avoid direct contact between the LD and the air and thus avoid carryover. These membrane-based devices can be flat plates (Abdel-Salam & Simonson, 2014) or hollow fiber heat and mass exchangers (N. Zhang et al., 2018; N. Zhang & Yin, 2017) Furthermore, an additional classification of absorption devices can be made based on their heat transfer characteristics. Most reviewed devices are adiabatic, where cooling of the LD takes place before entering the absorption device and the temperatures of LD and air converge along with the mass exchanger (Abdel-Salam & Simonson, 2014; Guan et al., 2020; Lee et al., 2021; Lee & Jeong, 2021; X. Liu et al., 2018; Peng & Luo, 2020; Sanaye & Taheri, 2018; Shan et al., 2018; Su et al., 2018; N. Zhang et al., 2018; N. Zhang & Yin, 2017; Q. Zhang et al., 2020). As improvement over adiabatic devices, some designs include internally cooled dehumidifiers. Internally cooled devices help maintain the temperature and the vapor pressure differential between the different fluids along the device (Guan et al., 2021; Liang et al., 2021; J. Liu et al., 2018, 2020).

3.3.2 Multistage dehumidification: As the temperatures of air and LD tend to converge along adiabatic dehumidifiers and regenerators, it diminishes the water vapor pressure differential between fluids that drives the mass exchange. To try to maintain a higher water vapor pressure differential in adiabatic devices, some authors have studied splitting the dehumidification and regeneration processes into sequential stages (N. Zhang et al., 2018; N. Zhang & Yin, 2017; Q. Zhang et al., 2020). By this method, the initial, more substantial differential can be maintained for the different stages. In addition to splitting the dehumidification process in several stages, the flow arrangement between air and LD inside open tower dehumidifiers (single and multistage arrangements) has been studied (Guan et al., 2021; Q. Zhang et al., 2020). The flow arrangements studied were counter, parallel, and cross-flow. The counter-flow arrangements can reach up to 29.8% and 26.4% higher system COP than cross and parallel flow arrangements. Nevertheless, the authors indicate the dependence of these results on operation conditions.

3.3.3 Dehumidification performance: The dehumidification performance and operation characteristics of the different designs of dehumidifiers analyzed is shown in Table 1. Dehumidification capacity is expressed as normalized Moisture Removal Rate (MRR) to compare systems with different supply air mass flow rates. Normalized MRR refers to MRR divided by the supply air mass flow rate. Table 1 shows a significant variation in dehumidification performance, independent of the type of dehumidifier considered. This is consistent with the large variation in the different reviewed systems' operation conditions and cooling capacity. From the large variation in normalized MRR for different dehumidifier types, it can be inferred that dehumidification performance is significantly affected by the system operation conditions, and that improvement of MRR must take into account both dehumidifier design and operation conditions.

Table 1: Dehumidification performance

Reference	**LD**	**Absorption device**	**OA humidity [g/kg]**	**OA temperature [C]**	**LD temperature [C]**	**LD concentration [%]**	**MRR normalized** $[kg/s]_{MRR}/[kg/s]_{air}$
(N. Zhang & Yin, 2017)	LiCl	Hollow fiber membrane	23.3	35	-	40	0.0208 - 0.0414
(Lee et al., 2021)	LiCL	Open tower, adiabatic	12	-	22.4-27.6	30	0.00194 - 0.00306
(Lee & Jeong, 2021)	LiCl		11	-	15.6-27.7	24.1-44.3	0.0021
(Guan et al., 2020)	LiBr		19	33.2	26.5	30-40	0.01
(Peng & Luo, 2020)	LiCl		28.9	35	22-23	22.6	0.0115 - 0.0135
(Q. Zhang et al., 2020)	NA		25.8	-	12.0-16.0	-	0.009
(X. Liu et al., 2018)	$CaCl_2$		21.3	-	12.7-17.4	28.7-34.1	0.0072 - 0.0081
(Guan et al., 2021)	LiBr	Open tower, internally cooled	21	-	26-36	41-49	0.0069 - 0.0127
(Liang et al., 2021)	LiBr		25	35	14	-	0.0003 - 0.002
(J. Liu et al., 2020)	LiBr		21.2	-	31.4	46.6	0.008
(J. Liu et al., 2018)	LiBr		20	-	35.9	NA	0.007 - 0.011

3.3.4 HP characteristics: The characteristics of the HP for the different systems reviewed are presented in Table 2. HP characteristics show significant differences due to the dehumidification systems' different characteristics and operating conditions. The operation conditions of the HP are selected to match the desired operating conditions for the overall system, rather than adapting the system to operate under the minimum possible temperature lift to provide the maximum possible COP from the HP. Considering that the energy inputs to the system are the energy for the HP compressor, fans, and pumps, reducing the energy requirements for the HP compressor could be an important design guideline for energy efficiency.
Improvement of the HP COP has been studied by using multistage HP (X. Liu et al., 2018) which aims to increase overall COP by reducing temperature lift. The HP COP range between 4.4/5.0 and 6.8/6.3 for each stage, for evaporator temperatures of 16.3/9.1 and 19.2/13.0 and condenser temperatures of 51.7/42.2 and 46.6/39.0.

Table 2: HP characteristics

Reference	Refrigerant	Evaporator temperature [C]	Condenser temperature [C]	Cooling capacity [kW]	COP
(Abdel-Salam & Simonson, 2014)	R134a	-	-	8.7 – 14.7	6.5-11.9
(Guan et al., 2020)	-	18-22.9	32.8-38.2	20.4-32.3	-
(Guan et al., 2021)	-	-	-	-	-
(Lee et al., 2021)	R410a	-	-	7.9	-
(Lee & Jeong, 2021)*	R410a	12	55	-	-
(X. Liu et al., 2018)*	R410a	9.1-19.2	39-52.8	74.4-89.2	4.4 - 6.8
(J. Liu et al., 2018)	-	-	-	33.8	5.1 – 7.6
(J. Liu et al., 2020)	-	20.9	49.3	48.6	6.2
(Q. Zhang et al., 2020)	-	10 - 15	41 - 54	54.5 - 59.1	3.8 - 4.3
(Liang et al., 2021)	R410a	12-17.5	32 - 36	293	-
(Peng & Luo, 2020)	R134a	-	-	290-280	9.8 - 10.9
(N. Zhang & Yin, 2017)	-	-	-	1.98	-
* Experimental work					

3.4 System integration

Integrating an HP to an LDD system can be difficult due to three challenges: HP load balancing, dehumidification and regeneration balancing, and variable outdoor conditions. Dehumidification and regeneration balancing and variable outdoor conditions are common to all types of LDD systems but balancing the HP heating and cooling loads and matching them to the instantaneous dehumidification and regeneration requirements during variable outdoor conditions represent a unique challenge to the development of HP-LDD systems.

3.4.1 HP capacity matching: Since the HP provides for cooling and heating loads, these loads must be balanced. Commonly, there is excessive heating capacity from the HP condenser that needs to be disposed of. An evaluated measure for capacity matching is to include additional heat exchangers, which reject the surplus heating capacity to the ambient air (Abdel-Salam & Simonson, 2014; Guan et al., 2020; Lee et al., 2021; Lee & Jeong, 2021; N. Zhang et al., 2018; N. Zhang & Yin, 2017). Excess heating capacity means that the LD concentration can increase higher than what is needed for dehumidification. To reduce the concentration of LD, the addition of water (Guan et al., 2020; Liang et al., 2021; J. Liu et al., 2018) and the mixing of concentrated and weak LD (Lee & Jeong, 2021) have been modeled and proved able to control the LD concentration.

3.4.2 Variable load conditions: To ensure comfortable conditions within the building, the dehumidification system must be able to modulate to match the target supply humidity at varying outdoor conditions and internal loads. A number of studies address the need for part-load operation and propose different dehumidification capacity modulation methods (Abdel-Salam & Simonson, 2014; Lee et al., 2021; Lee & Jeong, 2021; Liang et al., 2021; Sanaye & Taheri, 2018). Variable speed compressors can be used to control the mass flow rate in the evaporator and condenser (Abdel-Salam & Simonson, 2014; Lee et al., 2021; Liang et al., 2021; Sanaye & Taheri, 2018; N. Zhang & Yin, 2017). By controlling the cooling and heating capacity from the HP and maintaining the operation temperatures constant, it is possible to control the LD concentration to match the instantaneous dehumidification requirements. Alternatively, some studies analyze changes in the evaporator and condenser temperature to control the LD concentration (Abdel-Salam & Simonson, 2014; Liang et al., 2021). In addition, controlling the mass flow rate of refrigerant directed to the auxiliary condenser for capacity matching can modulate the LD concentration at the regenerator outlet (N. Zhang & Yin, 2017). Besides controlling the HP heating capacity, the mass flow rate of LD in the system has also been successfully evaluated as a capacity control method to match the required dehumidification load (Liang et al., 2021).

3.4.3 Energy performance: Efficiency for HP-LDD systems is commonly represented by the system COP. System COP refers to the change in enthalpy for the supply air inside the dehumidifier with respect to the electric power required by the system's HP and fluid circulation devices. Mathematically, it can be expressed by the Equation (1).

$$COP_{sys} = \frac{\dot{m}_a (h_{in} - h_{out})}{P_{electric}} \tag{1}$$

The effect of different variables over system COP has been parametrically evaluated. The assessed parameters can be classified as either design or operational. Operational parameters evaluated include the LD temperature entering the dehumidifier (Abdel-Salam & Simonson, 2014) and LD concentration entering the dehumidifier (Guan et al., 2020; X. Liu et al., 2018). The design parameters that have been evaluated are the dehumidifier mass exchange effectiveness (Abdel-Salam & Simonson, 2014; J. Liu et al., 2018), the LD heat recovery heat exchanger effectiveness (J. Liu et al., 2018; Peng & Luo, 2020), air and LD flow arrangement inside the dehumidifier (Guan et al., 2021; Q. Zhang et al., 2020) and multistage absorber and desorber (N. Zhang et al., 2018; N. Zhang & Yin, 2017; Q. Zhang et al., 2020). The values for system COP at nominal conditions and the results from the parametric analysis are shown in Table 3. Despite the large ranges in System COP reported by different authors, in general, it can be seen that open tower systems (adiabatic and internally cooled) present higher upper range values of COP in comparison with membrane-based systems. Nevertheless, the use of open tower absorbers is more common than the use of membrane-based absorbers, so more studies using membrane-based dehumidifiers are needed to establish a concrete relationship between dehumidifier type and system COP.

Table 3: System COP

Reference	**Evaluated parameters**	**System COP – nominal condition**	**System COP - range**
(Abdel-Salam & Simonson, 2014)	LD temperatures, Outdoor air conditions, mass transfer effectiveness	3.5	2.2 - 4.1
(N. Zhang & Yin, 2017)	Outdoor air conditions	-	1.5-2.75
(Guan et al., 2020)	Outdoor air conditions, LD concentration, HP load mismatch	Strategy 1: 3.4 Strategy 2: 4.1	Strategy 1: 3.5 - 3.25 Strategy 2: 3.9 - 4.5
(Lee et al., 2021)	-	2.26	-
(Lee & Jeong, 2021)	-	Case A: 1.4 Case B: 2.3	-
(X. Liu et al., 2018)	Outdoor air conditions, LD concentration	6.5	6.1-6.5
(Q. Zhang et al., 2020)	LD mass flow rate	Basic cross flow: 5.7	Cross flow: 6 Counter flow: 7.4
(Peng & Luo, 2020)	Heat exchangers effectiveness	-	3.5-7
(Guan et al., 2021)	Outdoor air conditions	Parallel flow: 4.5 Cross flow 4.7 Counter flow: 4.9	Parallel flow: 4.0-5.0 Cross flow: 4.3-6.1 Counter flow: 4.4-6.4
(X. Liu et al., 2018)	HP load mismatch, mass transfer effectiveness	5.96	4.19 -7.47

5. OUTLOOK FOR FUTURE RESEARCH

There are significant technical challenges that need to be solved before the HP-LDD system can become a suitable replacement for the VCR-based cooling and dehumidification systems. Further research should aim to solve the following technical challenges:

- Mismatch between the heating and cooling output of the heat pump and the heating and cooling demand of the LDD system. The common practice of rejecting the excess heating/cooling capacity to the outdoors can balance the unmatched capacity, but more energy-efficient alternatives must be found. A possible alternative is to store the excess capacity in the LD to form thermo-chemical energy storage (TCES)—the excess heating capacity can be used to regenerate the LD to a higher concentration. If excess cooling capacity is available, it can be used to precool the stored regenerated LD.
- Reliable control is needed to operate the HP-LDD systems, which are more complicated than the VCR-based cooling and dehumidification systems. The desired control must be able to modulate the system's sensible cooling and dehumidification capacity according to the instantaneous cooling and dehumidification demand while keeping the supply and the demand of the HP balanced. Therefore, the control will adjust the heat pump operation (e.g., the speed of the compressor) and the flow rate of the LD to ensure that supply air reaches the targeted temperature and humidity levels. Furthermore, the use of TCES for energy storage and capacity matching would require advanced predictive control methods to make the best use of the available heat pump capacity and the LD in the system.
- Corrosion due to carryover of the corrosive LD from the LDD systems. When considering the direct use of LD as heat transfer fluid in contact with the different system components, corrosion-resistant devices must be used. Alternatively, non-corrosive LD can be used. Among newly developed materials, Ionic Liquid Desiccants (ILD) have proven to be suitable alternatives for dehumidification (Wang et al., 2022). The high viscosity and cost of the new ILD put a significant barrier to using ILD as a replacement for conventional LDs, which use hygroscopic salts. A related issue to corrosion that must be addressed is the risk of carryover of the corrosive conventional LDs. The use of membrane-based dehumidifiers can solve the carryover issue, however, its use should be further studied to find devices or system configurations that can have similar or better dehumidification efficiency than the open tower dehumidifiers.

6. CONCLUSIONS

An overview of the state-of-the-art HP-LDD systems has been presented. The review covered general system configuration, components characteristics, and performance subjects. Finally, from this study, needs for future research were identified. The main findings of this review are summarized below.

1. Most systems reviewed in this study present a similar configuration—using single-stage dehumidifiers and regenerators, single-stage HP, and a liquid to a liquid heat exchanger for heat recovery.

2. Most of the reviewed LDD systems use open tower devices rather than membrane-based dehumidifiers. Among open tower devices, adiabatic and internally cooled dehumidifiers have been studied.

3. HP characteristics vary significantly according to system capacity, operation strategy (SSLC, total cooling or dehumidification only), and operation conditions. HP is usually selected based on the desired operating conditions of the HP-LDD system. However, these desired operating conditions may not be the optimal operating condition of the HP designed for typically heating and cooling purposes. Custom-designed HP for HP-LDD systems may help improve the overall efficiency of the HP-LDD systems.

4. Dehumidification performance shows a wide dispersion, even when using similar dehumidifiers. Overall, dehumidification performance depends not only on the dehumidifier type but also on operation conditions.

5. Given the variety of system configurations and operation conditions, it is difficult to generalize conclusions from different studies. However, in general, it can be seen that the use of open tower dehumidifiers (both adiabatic and internally cooled) leads to higher system COP than using membrane-based dehumidifiers. It should be noted that the membrane-based LDD is relatively new and is used in just a few previous studies. One advantage of membrane-based dehumidification is to eliminate the carryover of the corrosive conventional LD or the expensive new ILDs. It is possible that the dehumidification performance of membrane-based LDD can be improved with better membranes that have high permeability for water vapor but block any transport of LD/ILD through it.

6. Technical challenges remain to be solved to enable wide adoption of the HP-LDD systems. These technical challenges include making full use of the simultaneous heating and cooling output of the HP rather than rejecting the excess capacity to the ambient air—a waste of energy. The use of TCES can help solve this issue by using the excess heating capacity to regenerate LD at a higher concentration or using the excess cooling to cool the regenerated LD before it goes into the dehumidifier.

NOMENCLATURE

$\dot{m}$	mass flow rate	(kg/s)
h	enthalpy	(J/kg)
P	Electric power	(Watts)

Subscript

sys	system
a	air
in	inlet
out	outlet
electric	electric power use for heat pump, fans and pumps

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