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Abstract

Liquid desiccant cooling is being considered as an alternative to vapour compression air conditioning systems and has been extensively investigated in recent decades. The dehumidifiers and regenerators are the key components of liquid desiccant cooling systems and their heat and mass transfer performance significantly influences the performance of liquid desiccant cooling systems. This paper provides an overview of heat and mass transfer improvement techniques used to enhance the performance of direct-contact and indirect-contact dehumidifiers and regenerators used in liquid desiccant cooling systems. A number of techniques such as using a third heat transfer fluid, selection of packing materials, and tube arrangement, were reviewed and the performance of the dehumidifiers and regenerators using such techniques was summarised. The results showed that a large number of heat and mass transfer improvement techniques have been developed and used to enhance the performance of dehumidifiers and regenerators while further investigations on additives in liquid desiccants and surface modifications for direct-contact dehumidifiers and regenerators, and membrane deflection of indirect-contact dehumidifiers and regenerators might be still needed. In the meanwhile, design optimisation of packing materials (e.g. geometrical parameters) and fins with complex geometries for direct-contact dehumidifiers and regenerators, and inserts for indirect-contact dehumidifiers and regenerators may further improve their heat and mass transfer performance.

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A review of heat and mass transfer improvement techniques for dehumidifiers and regenerators of liquid desiccant cooling systems

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Abstract: Liquid desiccant cooling is being considered as an alternative to vapour compression air conditioning systems and has been extensively investigated in recent decades. The dehumidifiers and regenerators are the key components of liquid desiccant cooling systems and their heat and mass transfer performance significantly influences the performance of liquid desiccant cooling systems. This paper provides an overview of heat and mass transfer improvement techniques used to enhance the performance of direct-contact and indirect-contact dehumidifiers and regenerators used in liquid desiccant cooling systems. A number of techniques such as using a third heat transfer fluid, selection of packing materials, and tube arrangement, were reviewed and the performance of the dehumidifiers and regenerators using such techniques was summarised. The results showed that a large number of heat and mass transfer improvement techniques have been developed and used to enhance the performance of dehumidifiers and regenerators while further investigations on additives in liquid desiccants and surface modifications for direct-contact dehumidifiers and regenerators, and membrane deflection of indirect-contact dehumidifiers and regenerators might be still needed. In the

meanwhile, design optimisation of packing materials (e.g. geometrical parameters) and fins with complex geometries for direct-contact dehumidifiers and regenerators, and inserts for indirect-contact dehumidifiers and regenerators may further improve their heat and mass transfer performance.

Keywords: Liquid desiccant cooling; dehumidifier; regenerator; heat and mass transfer; improvement techniques.

Abbreviations

DRs	dehumidifiers and regenerators
HDPE	high-density polyethylene
HMT	heat and mass transfer
ICD	internally-cooled dehumidifier
IHR	internally-heated regenerator
LAMEE	liquid-to-air membrane energy exchanger
LD	liquid desiccant
LDC	liquid desiccant cooling
MTR	moisture transfer rate
PC	polycarbonate
PE	polyethylene
PP	polypropylene
PTFE	polytetrafluoroethylene
PVC	polyvinyl chloride
RIEC	regenerative indirect evaporative cooler
UALDD	ultrasonic atomisation liquid desiccant dehumidifier

1. Introduction

Desiccant cooling has been considered as a promising technology for cooling and dehumidification due to the fact that it can be driven by low-grade thermal energy and can deal with latent load efficiently [1-3]. Desiccant cooling generally includes solid desiccant cooling and liquid desiccant cooling (LDC). LDC using liquid desiccants (LDs) such as lithium chloride (LiCl), lithium bromide (LiBr), calcium chloride (CaCl₂), and triethylene glycol (TEG) as working solutions has been extensively studied [3-5]. In LDC systems, dehumidifiers and regenerators (DRs) are the major components and their heat and mass transfer (HMT) behaviours directly impact the overall performance of LDC systems. In the dehumidifier, the process air is dehumidified by the moisture absorption of the LD, which is driven by the vapour pressure difference between the process air and LD. The HMT process in the regenerator was opposite to that in the dehumidifier, in which the LD was concentrated in order to facilitate continuous dehumidification.

To evaluate the HMT performance of DRs, several performance indicators as summarised in Table 1 have been developed. Moisture transfer rate (MTR) is often used to evaluate the moisture transfer capacity of DRs [6-9]. Moisture transfer effectiveness (ϵ_m) is the ratio of the actual humidity ratio difference between the inlet air and outlet air to the maximum humidity ratio difference between the air and LD, which is often used to evaluate the mass transfer effectiveness of DRs [6-13]. Sensible effectiveness is defined in a similar way to the moisture transfer effectiveness, and is used to evaluate the heat transfer performance of DRs [11-13]. Both enthalpy effectiveness and total effectiveness are used to evaluate the overall HMT effectiveness of DRs [7, 11, 12, 14]. Enthalpy effectiveness is mainly used for direct-contact DRs [7, 14], while total effectiveness is often used for liquid-to-air membrane energy exchangers (LAMEEs) [11, 12]. Another performance indicator used is regeneration thermal efficiency, which represents the energy utilization efficiency of regenerators [15].

Table 1 Performance indicators and their definitions.

Performance indicator	Definition	Ref.
Moisture transfer rate (MTR)	$MTR = \dot{m}_a \times W_{a,in} - W_{a,out} $	[6-9]
Moisture transfer effectiveness (ε_m)	$\varepsilon_m = \frac{ W_{a,in} - W_{a,out} }{ W_{a,in} - W_{LD,in,eq} }$	[6-13]
Sensible effectiveness (ε_s)	$\varepsilon_s = \frac{ T_{a,in} - T_{a,out} }{ T_{a,in} - T_{LD,in} }$	[11-13]
Total effectiveness (ε_t)	$\varepsilon_t = \frac{\varepsilon_s + H^* \varepsilon_m}{1 + H^*}$	[11, 12]
Enthalpy effectiveness (ε_h)	$H^* = \frac{h_{fg}(W_{a,in} - W_{LD,in,eq})}{c_{p,a}(T_{a,in} - T_{LD,in})}$ $\varepsilon_h = \frac{ h_{a,in} - h_{a,out} }{ h_{a,in} - h_{LD,in,eq} }$	[7, 14]
Regeneration thermal efficiency (ε_r)	$\varepsilon_r = \frac{\dot{m}_a h_{fg}(W_{a,out} - W_{a,in})}{Q_{heating}}$	[15]

where $\dot{m}$ is the mass flow rate, W is the humidity ratio, T is the temperature, H^* is the operating factor, c_p is the specific heat capacity, h_{fg} is the latent heat of evaporation of water, h is the enthalpy, $Q_{heating}$ is the thermal energy input for the regeneration, and the subscripts a , LD , in , out , and eq indicate air, liquid desiccant, inlet, outlet, and equilibrium, respectively.

Over the last several decades, a number of HMT improvement techniques have been developed and employed to improve the HMT performance of DRs used in LDC systems. In a recent study, Wen and Lu [16] reviewed empirical correlations for mass transfer coefficients and moisture transfer effectiveness and reviewed five heat and mass transfer enhanced techniques including enhanced structures, surface modification, ultrasonic atomisation, membrane-based dehumidifier/regenerator and solution modification. However, there are many other HMT improvement techniques that have been developed and it seems that a comprehensive review of HMT improvement techniques developed for direct-contact and indirect-contact DRs used in LDC systems, and a comparison of their applications, benefits, and potential issues are still missing. This paper therefore aims to provide an overview of potential HMT improvement techniques developed for DRs and present a summary of technical merits and comparison of these techniques. The structure of this paper is as follows. Section 2

provides an overview of the HMT improvement techniques used for direct-contact DRs, in which HMT is achieved through direct contact between the process (or scavenging) air and LDs. Section 3 summarises the HMT improvement techniques developed for LAMEEs as indirect-contact DRs. Discussions on the major HMT improvement techniques are presented in Section 4. Some conclusive remarks are presented in Section 5, and challenges and future research directions in this field are provided in Section 6.

2. HMT improvement techniques for direct-contact DRs

The techniques used to improve the HMT performance of direct-contact DRs mainly include using a third heat transfer fluid, selection of flow configurations, selection of packing materials, surface modification and selection of surface materials, and adding additives in LDs.

2.1 Using a third heat transfer fluid

One of the main issues of adiabatic dehumidifiers is that the temperature of the LD increases along the flow direction of the LD due to the heat exchange with the air flow and the absorption heat. A similar issue also exists in adiabatic regenerators in which the LD is cooled by the air flow and the desorption of water vapour. The temperature change of the LD decreases the vapour pressure difference between the LD and air, and thus decreases the mass transfer driving force in DRs. These issues can be potentially solved by using a relatively large LD flow rate. However, it may increase the risk of carryover of LD droplets [17]. Internally-cooled dehumidifiers (ICDs) and internally-heated regenerators (IHRs) were therefore developed to solve these issues and improve the HMT between the LD and air [18].

Bansal et al. [19] experimentally compared the performance of a packed bed dehumidifier with a cooling coil embedded in the packing material. The results showed that the mass transfer effectiveness substantially increased by approximately 0.2 under the same inlet LD and air conditions by using cooling water, when compared to that without using cooling water. Gommed et al. [20] compared the performance of three dehumidifiers including an adiabatic

dehumidifier using cellulose structured packing, and two ICDs with a tube-bundle configuration respectively using Titanium tubes and high-density polyethylene (HDPE) tubes. In this particular comparison, it was shown that the adiabatic dehumidifier with a solution flow rate sufficient for good wetting outperformed the two ICDs. It was explained that this was probably resulted by a lower inlet solution temperature of the adiabatic dehumidifier than that of the two ICDs. Yin and Zhang [15] compared the performance of an IHR and an adiabatic regenerator both with a flat-plate configuration under the same inlet LD and air conditions. The simulation results showed that the regeneration thermal efficiency and MTR of the IHR were higher than those of the adiabatic regenerator under most of the simulation cases, while the similar performance was achieved by the two regenerators when a low air flow rate or a low LD flow rate was used. It was also found that the influence of the LD flow rate on the regeneration performance of the IHR was much less than that of the adiabatic regenerator, indicating that a relatively low LD flow rate could be used in the IHR without significantly compromising the regeneration performance. Liu et al. [21] compared the performance of three types of ICDs with different structures including parallel plates, finned-coils, and packed beds with cooling coils. The simulation results showed that the ICD with the finned-coil structure offered the best HMT performance while the packed bed with cooling coils showed the worst performance.

Fins are generally employed in ICDs and IHRs to increase the heat transfer area and improve the dehumidification and regeneration performance. Yin et al. [22] investigated the performance of a plate-finned heat exchanger. The experimental results showed that the mass transfer performance of this device using cooling water and heating water to represent an ICD and an IHR respectively was better than that without using cooling or heating water. Chung and Wu [23] compared the performance of an ICD using a finned-tube configuration to an adiabatic dehumidifier using a spray tower configuration. The experimental results showed that

the moisture transfer effectiveness of this improved dehumidifier increased by approximately 20% as compared to that of the dehumidifier using the spray tower configuration. The simulation results from Chen et al. [24] showed that the overall heat transfer coefficient of a plastic finned-tube dehumidifier using a modified polypropylene (PP) with thermal conductivity of 15 W/m K was about 95% of the titanium dehumidifier, and 84% of the aluminium or copper dehumidifier. Physical models were also used to simulate the HMT process between the air and LD in finned-tube heat exchangers [25, 26]. Fins were assumed as flat plates and fully wetted, and the influence of the tube geometry on the fluid flow was generally neglected in these models. It is noted that these assumptions may be invalid as partially wetting of the fin surface might happen when a low LD flow rate was used [27]. In addition, the tube geometry may also influence the surface wetting as observed in [28].

The advantages of ICDs and IHRs over adiabatic DRs have been demonstrated in the above-mentioned studies. However, the baselines used in these comparisons might not be solid. For instance, an extremely low cooling water temperature (4.8-8.7 °C) was used in [19], which is generally difficult to achieve in LDC systems without using chillers. Yin and Zhang [15] assumed the same HMT area between the air and LD for the internally-heated and adiabatic regenerators. The HMT area of the adiabatic regenerator could be larger than that of the IHR due to the saved space for heating fluid channels. On the other hand, an experimental investigation showed that an adiabatic dehumidifier outperformed two ICDs with the similar height [20]. Therefore, a more comprehensive and in-depth comparison between the internally-heated/cooled design and adiabatic design is necessary to provide a better understanding of the advantages and disadvantages of ICDs and IHRs. Although a number of studies investigated the performance of finned-tube heat exchangers and finned-plate heat exchangers as DRs, the research on the influence of fin design and configuration on the HMT performance is still limited, especially for fins with complex geometries. It has been stated in the previous studies

that using a third heat transfer fluid could reduce the LD flow rate and thereby reduce the risk of LD carryover [18]. However, there is still a lack of detailed guidelines that could be used to facilitate the design and operation of such DRs, in order to minimize the risk of LD carryover.

2.2 Selection of flow configurations

The previous studies on the investigation of flow configurations of adiabatic DRs, and ICDs and IHRs were reviewed in this section. The flow configurations of ICDs and IHRs are much more complicated than those of adiabatic DRs as a third heat transfer fluid was introduced into ICDs and IHRs.

2.2.1 Flow configurations of adiabatic DRs

The LD flow and air flow can be generally arranged in cross-flow, counter-flow, and parallel-flow, and the first two have been widely used in the majority of the previous studies. Liu and Jiang [29] and Liu et al. [30] compared the performance of adiabatic DRs using the above three flow configurations. The simulation results showed that the best regeneration performance when using the heated LD and dehumidification performance was always achieved by using the counter-flow configuration, while the best regeneration performance when using the heated air was achieved by using the parallel-flow configuration. The best mass transfer performance in dehumidifiers was also achieved by using the counter-flow configuration. The cross-flow configuration had a moderate mass transfer performance among the three configurations. Liu et al. [31] further revealed that the mass transfer performance of a regenerator using the heated LD was much better than that of a regenerator using the heated air.

The results from the above studies showed that the counter-flow configuration generally showed the best performance and the cross-flow configuration had a moderate performance. However, DRs using a cross-flow configuration were easy-to-install [32] and could potentially

alleviate desiccant carryover [14]. For a particular case, the flow configuration should be selected based on the practical design conditions.

2.2.2 Flow configurations of ICDs and IHRs

Ten flow configurations of ICDs and IHRs have been investigated in a number of studies [33-35], as summarised in Fig. 1. The LD usually flows downwards as it is generally driven by gravity in direct-contact DRs. Liu et al. [33] investigated six flow configurations (i.e. *a*, *d-f*, *i*, *j* in Fig. 1) of ICDs with a flat-plate design, in which the cooling water was circulated inside the flat plates. The simulations carried out based on a set of inlet air and LD conditions with different NTUs showed that mass transfer performance of the ICD with the same liquid desiccant-to-air flow configuration was close to each other (e.g. *d*, *e* and *f*, and *i* and *j* in Fig. 1). It was also found that the flow configurations of *i* and *j* outperformed the others while the differences among them were not significant. Peng and Luo [34] investigated the performance of IHRs with six flow configurations (i.e. *a*, *c*, *d*, *f*, *h*, and *j* in Fig. 1). The simulation results showed that the influence of the flow configuration was insignificant in comparison to that of the inlet concentration of the LD and the inlet temperature of the hot water. The counter-flow configuration between the LD and water and parallel-flow configuration between the LD and air were recommended. In a more recent study, Liu et al. [35] investigated the performance of ICDs using ten flow configurations as presented in Fig. 1. The simulation results showed that the flow configuration *e* outperformed the others under the most test cases as the temperature and vapour pressure differences in the dehumidifier using this flow configuration were more evenly distributed. However, the flow configuration *j* can be considered under lower LD flow rates or cooling water flow rates, or low inlet solution temperatures, or high inlet solution concentrations.

Fig. 1. Ten flow configurations investigated in [33-35].

The influence of the flow configuration on the performance of ICDs and IHRs might differ when refrigerants are used as the cooling and heating fluids respectively, as the temperature of the refrigerants is much more stable than that of water. Ali et al. [36] compared the performance of flat-plate DRs using parallel-flow and counter-flow configurations under the assumption of the constant plate temperatures. The simulation results showed that the parallel-flow configuration and counter-flow configuration generally provided better dehumidification performance and better regeneration performance, respectively. The results were different from those presented in [33, 34] and this might be explained by the assumption of the constant plate temperatures used.

The above studies were mainly carried out based on numerical simulations. However, experimental investigations on this topic were rarely found and experimental investigations might be able to provide additional information to better understand the HMT performance of such designs.

2.3 Selection of packing materials

Packing materials have been widely used in direct-contact DRs to provide the HMT area for working fluids. The packing materials should have a large void volume, a low bulk density, and good wettability, and the packing should provide a potentially large contact area for the LD and air and be chemically inert to the fluids being processed [37]. The packing materials used in DRs include random packing such as Berl saddles [38], Pall rings [39], and Rauschert Hiflow® rings [10, 40, 41], and structured packing such as wire meshes [42], cross-corrugated plates [43], and wood plate stacks [44]. The random packing can be placed in DRs without a specific method or orientation, while the structured packing needs to be arranged regularly in DRs. Compared to random packing, structured packing has advantages such as low pressure drops and easy installation [43], but it is generally more expensive than random packing. On the other hand, early studies stated that some random packing materials could provide a larger contact area per unit volume when comparing to structured packing [45].

The moisture transfer effectiveness and the specific MTR (i.e. MTR per cubic meter of the packing material) of the packing materials used in previous studies are presented and compared in Figs. 2 and 3, respectively. More details of the packing materials including the LDs used, the type and size of the packing material used, and the operating conditions for performance test can be found in Table 2. The packing materials presented in Figs. 2 and 3 were coded (e.g. a, b, c...) in order to match with those presented in Table 2. From Figs. 2 and 3, it can be observed that the ranges of the moisture transfer effectiveness and specific MTR of random packing were similar to those of the structured packing. However, the random packing materials were less frequently used in recent studies. This may be due to its relatively high pressure drop [43] and the potential risk of LD carryover resulted by the relatively large LD flow rate used as compared to the structured packing. In more recent studies, cross-corrugated cellulose plates such as Celdek 5090 and Celdek 7090 were frequently used in order to achieve

Fig. 2. Comparison of moisture transfer effectiveness of packing materials summarised in Table 2.

Fig. 3. Comparison of specific moisture transfer rate transfer of packing materials summarised in Table 2.

Table 2. Summary of packing materials and operating conditions as well as the resulted performance in direct-contact DRs.

Ref.	LD	Code*	Packings and DRs	Flow configuration	Operating conditions					Performance		
					$T_{a,in}$ (°C)	$W_{a,in}$ (g/kg)	$T_{LD,in}$ (°C)	X_{LD} (%)	Air flow rate (kg/s)	LD flow rate (kg/s)	MTR (g/s)	ε_m (%)
Löf et al [49]	LiCl	a	1-in. ceramic Raschig ring (random); 0.5 m (D) $\times$ 0.229 m (H).	Counter-flow	81-109	11.6-17.5	34-38	8.4-27.4 (ave.)	9.68-12.06 m ³ /min	5.68 L/min	1.64-2.33	50.0-66.4**
Patnaik et al. [50]	LiBr	b	Tripack No.1/2 polyethylene (PE) spheres (random); 0.81 m (D) $\times$ 0.4 m (H), tray distributor	Counter-flow	53.5-76.5	5.9-10.5	48.2-60.2	58.6-61.4	0.50-0.68	0.40-1.10	0.65-2.79	-
		c	Same as above but using spray nozzles		48.0-76.0	5.0-6.8	40.4-56.5	57.0-61.2	0.60-0.64	0.65-0.73	2.00-4.41	-
		d	Tripack No.1/2 polyethylene spheres (random); 0.81 m (D) $\times$ 0.4 m (H)		28.1-38.9	12.1-22.7	23.1-32.0	43.9-58.6	0.65-0.95	0.30-0.48	0.96-5.59	13.0-41.2**
Flaherty et al. [51]	LiBr	e	Tri-Packs No.1/2 polypropylene (random, 45 m ² /m ³); 0.81 m (D) $\times$ 0.40 m (H)	Counter-flow	-	19.6/21.2	25	54.9/55.0	0.78	0.66/1.46	4.52/11.62*	35.2/82.3**
		e	H = 0.28 m		-	19.0/18.4	35/25	52.8/55.0	0.78	0.66/1.46	3.98/7.80**	43.8/65.3**
		-	No packing (spray tower)		-	19.2/13.0	30/35	54.6/55.5	0.78	0.66/1.46	3.90/0.86**	33.9/14.7**
Chung et al. [52]	LiCl	f	1.6-cm polypropylene Flexi rings (random, 342 m ² /m ³); 0.1525 m (D) $\times$ 0.42 m (H)	Counter-flow	23.1-25.5	10.6-13.9	13.2-22.9	30-40	28-56 ft ³ /min	2.0-3.5 gal/min	0.070-0.237**	50.0-71.6
Chung [53]	TEG	g	Random packing	Counter-flow	-	-	-	90/95	25.0-40.0 ft ³ /min	1.50-2.80 gal/min	-	90.8-95.2
Chung and Ghosh [43]	LiCl	h	Cross-corrugated cellulose (structured, 410 m ² /m ³); 0.1525 m (D) $\times$ 0.4 m (H)	Counter-flow	24.4-29.6	13.1-17.8	19.1-21.0	30-38	27.5-44.0 ft ³ /min	2.0-3.5 gal/min	0.09-0.20**	62.0-68.0
		i	Cross-corrugated polyvinyl chloride (PVC) (structured, 223 m ² /m ³); 0.1525 m (D) $\times$ 0.41 m (H)		20.4-24.1	10.1-14.9	16.4-19.5	31-38	40-55 ft ³ /min	2.5-4.0 gal/min	0.11-0.23**	64.5-71.6
Potnis and Lenz [54]	LiBr	j	Polypropylene Tripack (random); 0.81 m (D) $\times$ 0.3 m (H)	Counter-flow	-	-	25	51	-	0.42-1.16	1.54-3.06	-
		k	Same as above		-	-	41	51	-	0.73-1.47	2.87-5.51	-
		l	Celdek (structured); 0.81 m (D) $\times$ 0.3 m (H)		-	-	25	51	-	0.54-1.16	1.22-2.28	-
		m	Same as above		-	-	41	51	-	0.75-1.28	0.78-1.19	-
		l	Celdek (structured); 0.81 m (D) $\times$ 0.55 m (H)		-	-	25	51	-	0.54-1.02	1.13-2.22	-
		m	Same as above		-	-	41	51	-	0.62-1.28	1.18-2.35	-
Öberg and Goswami [40]	TEG	n	2.54-cm polypropylene Rauschert Hiflow® rings (random, 210 m ² /m ³); 0.24 m (D) $\times$ 0.6 m (H)	Counter-flow	24.1-36.1	11.0-23.0	24.0-36.0	94.0-96.1	0.44-1.56 kg/(m ² s)	4.48-6.59 kg/(m ² s)	0.19-0.71	73.8-94.0
		n	Same as above but H = 0.4, 0.6, and 0.8 m		30	16.5	30	95	1.0 kg/(m ² s)	5.5 kg/(m ² s)	0.37, 0.41, and 0.44	72.7, 87.2, and 89.7

Martin and Goswami [41]	TEG	o	2.54-cm polypropylene Rauschert Hiflow® rings (random, 210 m ² /m ³); 0.24 m (D) × 0.6 m (H)	Counter-flow	30.0-51.1	10.3-25.0	60.0-71.1	92.8-95.1	0.41-1.46 kg/(m ² s)	4.29-6.44 kg/(m ² s)	0.37-1.13	59.3-98.3
		o	Same as above but H = 0.4, 0.6, and 0.8 m		40	17.5	65	94	1.0 kg/(m ² s)	5.2 kg/(m ² s)	0.66, 0.71, and 0.83	66.1, 70.1, and 79.4
Fumo and Goswami [10]	LiCl	p	1-in. polypropylene Rauschert Hiflow® rings (random, 210 m ² /m ³); 0.24 m (D) × 0.6 m (H)	Counter-flow	29.9-40.1	14.2-21.5	25.0-35.2	33.1-34.9	0.890-1.513 kg/(m ² s)	5.019-7.420 kg/(m ² s)	0.21-0.53	54.1-76.7**
		q	Same as above		29.4-40.0	14.3-21.0	60.3-70.0	32.8-34.9	0.833-1.438 kg/(m ² s)	5.185-7.541 kg/(m ² s)	1.36-2.45	76.3-96.2**
Sultan et al. [55]	CaCl ₂	r	Z-shaped plastic packing (random, 160 m ² /m ³); 0.15 m (W) × 0.15 m (L) × 0.60 m (H) [56]	Counter-flow	62.8-112.6	11.6-17.2	28.0-39.9	39.3-47.2	0.0052-0.0232	0.0016-0.0077	0.07-0.23	-
Zurigat et al. [44]	TEG	s	Arrays of wood plate stack (structured, 77 m ² /m ³); 0.48 m (H) × 0.0225 m ² (cross-section area***)	Counter-flow	25.4-44.0	16.2-20.7	28.2-45.5	93.0-98.0	1.50-2.61 kg/(m ² s)	0.13-0.82 kg/(m ² s)	0.111-0.233	19.0-43.1
		t	Arrays of aluminium plate stack (structured, 77 m ² /m ³); 0.48 m (H) × 0.0225 m ² (cross-section area***)		25.6-40.7	16.0-21.8	25.0-43.2	93.0-98.0	1.50-2.61 kg/(m ² s)	0.13-0.82 kg/(m ² s)	0.101-0.256	18.7-46.3
Abdul-Wahab et al. [45]	TEG	u	Arrays of wood plate stack oriented 90° to each other (structured, 77 m ² /m ³); 0.48 m (H) × 0.0225 m ² (cross-section area***)	Counter-flow	25.4-44.0	-	28.2-45.5	93.0-95.2	1.50-2.61 kg/(m ² s)	0.13-1.00 kg/(m ² s)	0.12-0.22	18.9-43.7
		v	Same as above but specific surface area is 100 m ² /m ³		30.8-40.4	-	28.0-33.6	93.0-98.0	2.07-2.60 kg/(m ² s)	0.13-0.64 kg/(m ² s)	0.12-0.28	12.8-34.6
		w	Same as above but specific surface area is 200 m ² /m ³		25.0-40.0	-	31.0-39.0	93.0-97.6	1.96-2.60 kg/(m ² s)	0.13-0.64 kg/(m ² s)	0.13-0.30	14.6-68.1
Longo and Gasparella [39]	LiCl	x	25 mm plastic Pall Rings (random); 0.4 m (D) × 0.725 m (H)	Counter-flow	24.3-37.6	7.3-23.3	23.4-24.0	39.2-40.6	0.43-0.47 kg/(m ² s)	0.10-1.17 kg/(m ² s)	0.08-0.95**	34-93****
		y	Same as above		48.2-50.1	4.0-12.3	49.9-50.5	39.1-39.3	0.38-0.42 kg/(m ² s)	0.14-1.23 kg/(m ² s)	0.18-0.78**	22-80****
	LiBr	z	Same as above		23.6-36.7	8.2-22.8	23.7-53.9	51.9-53.9	0.44-0.47 kg/(m ² s)	0.16-1.39 kg/(m ² s)	0.15-1.03**	34-93****
		aa	Same as above		50.0	3.0-15.4	48.0-49.5	50.1-51.3	0.40-0.44 kg/(m ² s)	0.16-1.46 kg/(m ² s)	0.12-0.95**	22-80****
	KCO OH	ab	Same as above		22.6-35.8	8.8-20.7	21.9-24.8	72.8-74.0	0.48-0.52 kg/(m ² s)	0.09-1.23 kg/(m ² s)	0.12-0.85**	34-93****
		ac	Same as above		50.0	2.8-14.5	46.9-50.6	75.5-75.9	0.41-0.44 kg/(m ² s)	0.13-1.32 kg/(m ² s)	0.14-0.92**	22-80****
Abu-Arabi et al. [57]	TEG	ad	Arrays of wood plate stack (structured, 200 m ² /m ³); 0.48 m (H) × 0.0225 m ² (cross-section***)	Counter-flow	31-40	11.2-17.4	45-57	89.0-91.0	0.5-3.0 kg/(m ² s)	0.51-3.16 kg/(m ² s)	0.193-0.574	56.0-99.5

Elsarrag [58]	TEG	ae	Cellulose rigid media pads (structured, 440 m ² /m ³); 0.55 m (H) × 0.09 m ² (cross-section)	Counter-flow	-	18.2-24.3	72.0-79.2	90.4-95.0	1.04-1.22 kg/(m ² s)	0.65-1.56 kg/(m ² s)	1.578-4.011	23.0-38.0
Liu et al. [59]	LiBr	af	Celdek 7090 (structured, 396 m ² /m ³); 0.55 m × 0.4 m × 0.35 m	Cross-flow	26.8-32.7	12.0-17.3	21.2-27.8	42.8-48.0	0.328-0.453	0.31-0.64	1.08-2.31**	41.3-68.0
Liu et al. [60]	LiBr	ag	Celdek 7090 (structured, 396 m ² /m ³); 0.55 m (H) × 0.4 m (L) × 0.35 m (W)	Cross-flow	26.8-32.7	12.0-17.3	21.1-27.8	42.8-48.3	1.13-2.35 kg/(m ² s)	2.18-4.54 kg/(m ² s)	1.03-2.29	42.0-68.3
Moon et al. [32]	CaCl ₂	ah	Cross-corrugated cellulose paper sheets (structured, 608 m ² /m ³); 0.3 m × 0.3 m (cross-section area)	Cross-flow	26.8-39.1	16.4-24.4	26.2-38.2	32.8-43.0	0.92-1.99 kg/(m ² s)	0.54-3.18 kg/(m ² s)	0.48-1.24	43.6-77.8
Zhang et al. [61]	LiCl	ai	Cross-corrugated ceramic packing (structured, 550 m ² /m ³); 0.25 m (H) × 0.25 m (W) × 0.25 m (L)	Cross-flow	34.5-35.6	14.9-15.3	14.0-16.8	29-35	0.0328-0.0653	0.0067-0.0143	0.142-0.421**	22.3-57.2**
		aj	Same as above		44.1-46.7	14.9	54.8-55.9	31-37	0.0332-0.0655	0.0098-0.023	0.090-0.349**	9.8-27.6**
Kumar et al. [42]	CaCl ₂	ak	Wire mesh packing, 36 layers (structured); 0.3 m (W) × 0.3 m (L) × ~0.18 m (H)	Counter-flow	35.0-44.8	18.0-27.1	33.2-38.8	38.6-41.3	0.024-0.048	0.043-0.071	0.05-0.20	26.1-55.2
		al	Same as above but using 75 layers of meshes		-	20.3-23.1	-	-	0.024-0.033	0.047-0.075	0.16-0.18**	23.7-63.1
		am	Same as above but using 6 layers of meshes		-	18.9-27.0	-	-	0.021-0.039	0.045-0.074	0.13-0.19**	30.7-56.0
		-	No packing (spray tower)		-	20.6-26.9	-	-	0.023-0.047	0.044-0.073	0.12-0.13**	20.2-46.8
Bassuoni [62]	CaCl ₂	an	Cross-corrugated plate (structured, 390 m ² /m ³); 0.35 m (H) × 0.35 m (L) × 0.2 m (W)	Cross-flow	~31	~18	15-30	34-48	0.022-0.144	0.014-0.058	0.22-0.70	38.5-74.9
		an	Same as above but thickness = 0.1 m		~31	~18	-	-	0.022-0.140	-	0.24-0.45	45.0-57.0
		ao	Cross-corrugated plate (structured, 390 m ² /m ³); 0.35 m (H) × 0.35 m (L) × 0.2 m (W)		~31	~18	53-84	27-38	0.022-0.144	0.014-0.058	0.21-0.67	32.9-73.9
		ao	Same as above but thickness = 0.1 m		~31	~18	-	-	0.022-0.140	-	0.25-0.42	58.8-68.3
Gao et al. [63]	LiCl	ap	Celdek packing (structured, 396 m ² /m ³); 0.5 m (H) × 0.3 m (W) × 0.5 m (thickness)	Cross-flow	27.7-38.8	9.3-23.3	25.0-46.1	32-40	0.08-0.14	0.10-0.27	0.13-1.15**	39.6-73.2
Mohamed et al. [46]	LiCl	aq	Gauze packing (structured, 400 m ² /m ³); 0.4 m (H) × 1.0 m (L) × 0.4 m (W)	Cross-flow	28.0-44.0	12.0-24.0	15.0-45.0	32.0-40.0	0.08-0.25	0.05-1.75	0.14-2.38**	64.7-86.9
		aq	Gauze packing (structured, 400 m ² /m ³); 0.4 m (H) × 0.5 m (L) × 0.4 m (W)		28.0-44.0	12.0-24.0	15.0-45.0	32.0-40.0	0.08-0.14	0.05-0.30	0.09-1.26**	35.9-70.5
Wang et al. [7]	LiCl	ar	Celdek 5090 (structured, 650 m ² /m ³); 0.4 m (H) × 0.3 m (L) × 0.3 m (W)	Counter-flow	24.8-40.5	10.6-25.1	16.4-35.3	31.7-40.1	0.046-0.080	0.017-0.114	0.19-0.87	33.9-69.4
		ar	Same as above, but H = 0.3, 0.4, and 0.5 m		29.9-30.0	16.9-17.2	21.2-21.3	35.6-35.8	0.078-0.079	0.083	0.54, 0.58, and 0.59	53.1, 57.6, and 59.9

		ar	Same as above, but H = 0.3, 0.4, and 0.5 m		29.9-30.0	16.7-16.9	21.1-21.3	35.5-35.7	0.078-0.079	0.050-0.051	0.46, 0.50, and 0.51	47.5, 50.3, and 51.8
Cihan et al. [64]	LiCl ₂ with BYK 349	as	Polycarbonate (PC) panels with thickness and channel angle of 6 mm and 30° (structured); 0.6 m (H) × 0.3 m (L) × 0.3 m (W)		-	-	28.7 (ave.)	38-43	0.1058-0.2645	1.42-1.85	0.496-1.749**	69.0-85.1
		at	Panels with a thickness of 6 mm and a channel angle of 45°		-	-	28.7 (ave.)	38-43	0.1058-0.2645	1.42-1.85	0.404-0.751**	31.8-52.8
		au	Panels with a thickness of 6 mm and a channel angle of 60°	Counter-flow	-	-	28.7 (ave.)	38-43	0.1058-0.2645	1.42-1.85	0.339-0.698**	36.1-47.1
		av	Panels with a thickness of 10 mm and a channel angle of 30°		-	-	28.7 (ave.)	38-43	0.1058-0.2645	1.42-1.85	0.511-1.126**	40.7-57.9
		aw	Panels with a thickness of 10 mm and a channel angle of 45°		-	-	28.7 (ave.)	38-43	0.1058-0.2645	1.42-1.85	0.371-1.251**	31.8-56.4
		ax	Panels with a thickness of 10 mm and a channel angle of 60°		-	-	28.7 (ave.)	38-43	0.1058-0.2645	1.42-1.85	0.350-0.976**	45.9-56.0
Dong et al. [65]	LiCl	ay	Corrugated hardboard (structured, 537.3 m ² /m ³); 0.3 m × 0.3 m × 0.5 m		27-34	17	21.4	36	0.071	0.051-0.116	0.491-0.562	51.4-62.8
		az	S-shape PVC (structured, 81.8 m ² /m ³); 0.3 m × 0.3 m × 0.5 m	Counter-flow	27-34	17	21.4	36	0.071	0.051-0.116	0.316-0.383	34.5-41.9
		ba	Globular-shape polypropylene; (structured, 77.2 m ² /m ³); 0.3 m × 0.3 m × 0.5 m		27-34	17	21.4	36	0.071	0.051-0.116	0.268-0.332	29.2-36.3
Chen et al. [6]	LiCl	bb	Z-type gauze packing way 1 (structured, 160 m ² /m ³); 0.34 m (L) × 0.34 m (W) × 0.5 m (H)		34.9-35.3	21.9-22.6	19.4-20.1	39	0.13-0.26	0.25-0.26	0.797-1.113	28.6-37.5
		bc	Z-type gauze packing way 2 (structured, 160 m ² /m ³); 0.34 m (L) × 0.34 m (W) × 0.5 m (H)		34.9-35.6	21.5-22.6	14.5-24.5	39	0.13-0.28	0.13-0.53	1.039-2.007	25.0-41.7
		bd	Plant fibre packing (structured, 450 m ² /m ³); 0.34 m (L) × 0.34 m (W) × 0.5 m (H)		34.9-35.6	21.5-22.6	14.5-24.5	39	0.13-0.28	0.13-0.53	1.333-2.706	37.9-55.8
		be	Cellulose corrugated packing (structured, 500 m ² /m ³); 0.34 m (L) × 0.34 m (W) × 0.5 m (H)	Cross-flow	34.9-35.6	21.5-22.6	14.5-24.5	39	0.13-0.28	0.13-0.53	1.448-3.143	37.2-57.0
		bf	Z-type gauze packing way 2 (structured, 160 m ² /m ³); 0.34 m (L) × 0.34 m (W) × 0.5 m (H)		35.2-35.9	21.0-23.5	55.5-65.5	32	0.14-0.28	0.20-0.52	0.297-1.099	5.1-13.1
		bg	Plant fibre packing (structured, 450 m ² /m ³); 0.34 m (L) × 0.34 m (W) × 0.5 m (H)		35.2-35.9	21.0-23.5	55.5-65.5	32	0.14-0.28	0.20-0.52	0.497-2.003	10.3-24.7
		bh	Cellulose corrugated packing (structured, 500 m ² /m ³); 0.34 m (L) × 0.34 m (W) × 0.5 m (H)		35.2-35.9	21.0-23.5	55.5-65.5	32	0.14-0.28	0.20-0.52	1.397-2.784	22.1-38.8

Varela et al. [66]	LiCl	bi	Structured packing (460 m ² /m ³); 0.1 m (W) × 0.2 m (L) × 0.4 m (H)	Cross-flow	33.92-34.06	19.40-19.60	16.90-17.12	29.18-30.19	0.44-2.38 m/s	0.039-0.188	-	44.4-85.7**
		bj	Same as above		33.09-34.08	19.34-19.64	49.92-50.12	29.79-30.14	0.41-2.30 m/s	0.044-0.199	-	14.9-54.8**
Kumar and Asati [67]	CaCl ₂	bk	Celdek corrugated cellulose packing (structured, 390 m ² /m ³); 0.57 m × 0.27 m × 0.34 m	Counter-flow	30.6-39.4	16.0-20.0	25-35	36-42	0.024-0.072	0.056-0.112	-	31.7-71.3
		bl	Same as above		32.0-44.2	24.0-28.2	50.0-65.0	35.4-40	0.024-0.072	0.056-0.112	-	26.1-61.4

* The same code was given for the same packing material with different sizes used in the same study but different codes were given for the same packing material used for dehumidification and regeneration in the same study.

** Calculated based on the experiment results reported, and vapour pressure of LDs was determined based on [68, 69] if needed.

*** Cross-section area was calculated based on the experimental results.

**** Experiment results for different LDs used were not provided.

***** Cells shaded indicated that the packing materials were used in regenerators, and the cells without shading indicated the dehumidifiers. where X is the mass fraction.

2.4 Surface modification and selection of surface materials

The wetted area and wettability of the solid surface in direct-contact DRs can be improved by modifying the solid surface or selecting proper materials for the surface. Qi et al. [70] investigated the influence of the surface roughness, solution temperature, solution concentration, and a TiO₂ hydrophilic surface coating on the contact angle, wetted area, and MTR in a regenerator with a flat-plate configuration. The results showed that the contact angle substantially decreased by using the TiO₂ hydrophilic surface coating, which significantly increased the wetted area and MTR. Substantial increases in the wetted area, MTR, and moisture transfer effectiveness were also observed in an ICD [71] using TiO₂ coatings when compared to those without using the surface coating. Durability tests of three different types of stainless-steel plates (i.e. SUS304, SUS316 and SUS410) coated with TiO₂ showed that SUS304 with TiO₂ coating showed good resistance to LiBr desiccant solution (30 wt%) [72]. It is noted that the TiO₂ coating used needs to be periodically illuminated by ultraviolet light with relatively small electricity consumption in order to activate the coating [72]. Plasma surface treatment was also considered as a technique to increase the surface wettability of dehumidifiers [73, 74]. For instance, Dhiman et al. [73] developed an adiabatic dehumidifier with a flat-plate configuration using polymer membranes with plasma surface treatment. The wetting factor was not directly evaluated in this study and the experimental test showed that negligible carryover was achieved under most of the test cases.

The performance of two ICDs with a tube-bundle configuration using Titanium tubes and HDPE tubes respectively was experimentally evaluated by Gommed et al. [20]. The observation during the experiments showed that the Titanium tubes outperformed the HDPE tubes in terms of the wettability of the LD on the surface of the tubes. The wettability and dehumidification performance of the ICDs using polytetrafluoroethylene (PTFE), Stainless steel, and Titanium plates were tested by Dong et al. [75]. The results showed that the highest

wetted area was obtained by the dehumidifier using the Titanium plate. The highest MTR and moisture transfer effectiveness were also obtained by the dehumidifier using the Titanium plate. Dong et al. [75] also found that the Titanium plate had the highest surface free energy, which can offer a better surface wettability. The surface modification techniques and different surface materials used to improve the HMT performance of DRs are summarised in Table 3.

The above studies on the surface modification and surface materials mainly focused on DRs with the flat-plate and tube-bundle configurations. The investigation of the surface modification and the surface materials of DRs with complex structures such as packing materials and finned-tube is rarely found. The studies focusing on the durability of the surface modification techniques are still limited. Titanium showed great potential as the surface material of DRs due to its high surface free energy and good corrosion resistance to LDs. However, it is generally expensive. The plastic with surface modification may be worthwhile to be further investigated.

Table 3. Surface materials and surface modification for HMT improvement.

Ref.	Surface material and modification methods	LD	DRs and configuration	Inlet conditions of experiments	Key findings
Qi et al. [70]	Stainless steels (SUS316) with roughness of 393.8, 287.4, 147.4, and 82.7 nm; Stainless steel (SUS316) with TiO ₂ hydrophilic coating.	LiCl, LiBr	Regenerator; Flat-plate; Size was not provided.	$T_{a,in}$: 23.8 °C; $W_{a,in}$: 9.41/9.45 g/kg; $T_{LD,in}$: 37.4-57.2 °C; X_{LD} : 27.9%/28.0%; $\dot{m}_a$: 0.15 kg/s; $\dot{m}_{LD}$: 0.062/0.064 kg/s T_{plate} : 35.4/35.5 °C	Contact angles of LiCl and LiBr decreased with the increase of the roughness when it was above 100 nm; Contact angle, wetted area, and MTR of LiCl reduced by 53.8%, increased by 30-40% and improved by 200%-300% when using the hydrophilic coating.
Dong et al. [71]	Stainless steel; Stainless steel with an inorganic compact protective layer and TiO ₂ superhydrophilic coating.	LiCl	ICD; Flat-plate; Counter-flow; 0.55 m (L) × 0.10 m (W) × 0.60 m (H); Only one plate.	$T_{a,in}$: 23.6-38.7 °C; $W_{a,in}$: 10.9-26.2 g/kg; $T_{LD,in}$: 23.1-30.5 °C; $T_{hft,in}$: 15.6-24.9 °C; $\dot{m}_a$: 0.027-0.07 kg/s; $\dot{m}_{LD}$: 0.01-0.049 kg/s; $\dot{m}_{htr}$: 0.03-0.10 kg/s; X_{LD} was not provided	Contact angle of LiCl on the coated surface was 10.4% of that on the uncoated surface; MTR and ε_{deh} increased by 60% and 63% respectively by using coating.
Qi et al. [72]	Stainless steels (SUS304, SUS316, SUS410); Stainless steels (SUS304, SUS316, SUS410) with TiO ₂ superhydrophilic self-cleaning coating.	LiBr	-	-	Contact angles of LiBr on the coated surfaces of SUS304, SUS316, and SUS410 were 16.4%, 19.7%, and 25.5% of those on the uncoated surfaces respectively; SUS304 and SUS316 with coating showed good durability and good corrosion resistance performance.
Lee et al. [76]	Grooved ABS plate with hydrophilic coating (acrylic epoxy resin: thinner: alumina oxide powders = 1:0.5:0.35 wt.).	LiCl	ICD; Grooved-plate; Counter-flow; 0.2 m (L) × 0.6 m (H); Only one plate.	$T_{a,in}$: 35 °C; $RH_{a,in}$: 70%/80%; $T_{LD,in}$: 40 °C; X_{LD} : 39.8%; $T_{hft,in}$: 32 °C v_a : 0.7-1.3 m/s; $\dot{m}_{LD}$: 0.005-0.011 kg/s; $\dot{m}_{htr}$: 0.01 kg/s	-
Dhiman et al. [73]	Microporous polymer membrane; Plasma surface treatment using a mixture of 2% silane gas in argon, with oxygen in a MARC2 plasma system.	LiCl	Adiabatic DR; Flat-plate; Cross-flow; 0.305 m (H) × 0.267 m (W) × 0.165 m (depth); 86 sheets.	$T_{a,in,deh}$: 35 °C; $RH_{a,in,deh}$: 49%; $T_{LD,in,deh}$: 19.4-20.2 °C; $X_{LD,deh}$: 31%-32.3%; $V_{a,deh}$: 10-50 CFM; $V_{LD,deh}$: 1.93-2.55 LPM;	Membrane surface was oxidised and consisted of silicon oxides, silicon hydrides, and/or silicon hydroxides; Negligible LD carryover was achieved in most test cases for the adiabatic dehumidifier using the plasma-treated polymer membranes.

Prieto et al. [74]	Polypropylene (PP); PP with a plasma surface treatment with plasma nano-layer depositions of acrylic acid.	LiCl	ICD; Tube-bundle; Counter-flow; 78 tubes with a length of 0.325 m and an outer diameter of 6.5 mm.	$T_{a,in,reg} : 25\text{ }^{\circ}\text{C};$ $RH_{a,in,reg} : 35\%-50\%;$ $T_{LD,in,reg} : 39.3\text{-}40.3\text{ }^{\circ}\text{C};$ $X_{LD,reg} : 30.5\%-32\%;$ $V_{a,reg} : 10\text{-}50\text{ CFM};$ $Y_{LD,reg} : 1.67\text{-}2.7\text{ LPM}$ $T_{a,in} : 27.0\text{-}33.6\text{ }^{\circ}\text{C};$ $RH_{a,in} : 33.2\%\text{-}48.5\%;$ $T_{LD,in} : 17.0\text{-}25.0\text{ }^{\circ}\text{C};$ $X_{LD} : 35.3\%\text{-}35.9\%;$ $T_{hft,in} : 8.7\text{-}17.9\text{ }^{\circ}\text{C}$ $v_a : 0.99\text{-}2.10\text{ m/s};$ $V_{LD} : 113.3\text{-}343.8\text{ L/h}$ $V_{htf} : 220.7\text{-}423.5\text{ L/h}$ $T_{a,in} : 35/39\text{ }^{\circ}\text{C};$ $W_{a,in} : 33.9/30\text{ g/kg};$ $T_{LD,in} : 30/23\text{ }^{\circ}\text{C};$ $X_{LD} : 40\%;$ $\dot{m}_a : 0.037/0.011\text{ kg/s};$ $\dot{m}_{LD} : 0.070/0.022\text{ kg/s}$	MTR was substantially increased when using the PP tubes with plasma surface treatment.
Hassan and Hassan [77]	Fibrous sheet attached to inner surfaces of the fluid channel.	CaCl ₂	Adiabatic dehumidifier; Concentric tube; Counter-flow; ~1 m (H) $\times$ ~0.3 m (D).	$T_{a,in} : 35/39\text{ }^{\circ}\text{C};$ $W_{a,in} : 33.9/30\text{ g/kg};$ $T_{LD,in} : 30/23\text{ }^{\circ}\text{C};$ $X_{LD} : 40\%;$ $\dot{m}_a : 0.037/0.011\text{ kg/s};$ $\dot{m}_{LD} : 0.070/0.022\text{ kg/s}$	The surface was completely wetted by utilising the capillary effect of the fibres on LD; The maximum deviation of the measured LD flow rates at the outlet of the dehumidifier was less than 5%, indicating good wettability.
Gomm et al. [20]	Titanium; HDPE.	LiCl	ICD; Tube-bundle; Counter-flow; structured packing with 0.20 m height and tube bundle with 0.23 m height.	$T_{a,in} : 30\text{ }^{\circ}\text{C};$ $W_{a,in} : 19.0\text{ g/kg};$ $T_{LD,in} : 40\text{ }^{\circ}\text{C};$ $X_{LD} : 40\%;$ $\dot{m}_a : 0.3\text{ kg/s};$ $\dot{m}_{LD} : 0.3\text{ kg/s};$ Others were not provided*	Titanium tubes showed a better surface wettability than that using HDPE tubes according to direct observation.
Dong et al. [75]	PTFE; Stainless steel; Titanium.	Not provided	ICD; Flat-plate; Counter-flow; 0.55 m (L) $\times$ 0.05 m (W) $\times$ 0.60 m (H); One plate.	$T_{a,in} : 28.3\text{-}40.2\text{ }^{\circ}\text{C};$ $W_{a,in} : 13.9\text{-}24.6\text{ g/kg};$ $T_{LD,in} : 18.1\text{-}30.2\text{ }^{\circ}\text{C};$ $T_{hft,in} : 16.6\text{-}25.9\text{ }^{\circ}\text{C};$ $\dot{m}_a : 0.028\text{-}0.079\text{ kg/s};$ $\dot{m}_{LD} : 0.015\text{-}0.046\text{ kg/s};$ Others were not provided	Titanium showed the best surface wettability among the three materials; Compared to a dehumidifier using the PTFE plate with a surface energy of 30.34 mJ/m ² , MTR and ε_{deh} increased by 37.4% and 33.8% respectively when using the Titanium plate with a surface free energy of 50.61 mJ/m ² .

* Reference values of inlet conditions were provided while the full ranges of the inlet conditions were not provided.

where RH is the relative humidity, V is the volumetric flow rate, v is the velocity, and the subscript htf indicates heat transfer fluid.

2.5 Adding additives in liquid desiccants

Additives have been used to improve the thermal conductivity and surface wettability of LDs [78-80], and reduce the causticity of the LD on metals [81]. Ali et al. [36, 78] investigated the performance of CaCl_2 desiccant solution enhanced by Cu-ultrafine particles in an ICD and an IHR with a flat-plate configuration. The simulation results showed that the improvement of HMT performance by adding nanoparticles was insignificant as the desiccant film was thin and the increase of LD thermal conductivity had an insignificant impact on the performance of the ICD and the IHR [36]. Wen et al. [80] investigated the dehumidification performance of LiCl desiccant solutions with multi-walled carbon nanotubes (MWNTs) and polyvinyl pyrrolidone (PVP) surfactant, and with PVP surfactant only. The test results based on an ICD with a flat-plate configuration showed that the MTR increased by 26.1% and 25.9% on average for the LDs with the PVP surfactant only and with the MWNTs and surfactant, respectively. It was concluded that the performance improvement was due to the significant increase of the wetted area on the flat plate. The improvement of the LD with the MWNTs and surfactant was attributed to the surfactant only, and adding 0.1 wt% MWNTs showed an undetected effect.

Surfactants have been considered as another type of additives to improve the HMT performance of DRs as the surface tension of LDs can be reduced and the wettability of LDs on the surface can be improved by adding proper surfactants [64]. Cihan et al. [64] experimentally investigated the performance of an LDC system using LiCl desiccant solutions with a polyether modified siloxane surfactant (BYK349). An adiabatic dehumidifier and an adiabatic regenerator with structured packing were used. It was observed that the wetted area increased when using the LD with the surfactant while foaming problems existed in the DR, which deteriorated the mass transfer performance. The performance of LiCl desiccant solutions with the polyvinyl pyrrolidone (PVP-K30) surfactant in an ICD with a flat-plate configuration was investigated in [79]. The results showed that the contact angle of the desiccant solution on

the plate (i.e. stainless steel 316L) decreased from 58.5° to 28.0° by adding 0.4% mass fraction of PVP-K30 into the LiCl desiccant solution and the wetted area of the DR was substantially increased. Compared to the LiCl desiccant solution without the surfactant, the MTR and moisture transfer effectiveness in the dehumidifier increased by 22.7% and 19.9% on average respectively, when using the LD with the surfactant. In another study [81], hydroxyethyl urea with a mass fraction of 39% was used as the additive of the LiCl desiccant solution to reduce its causticity. The experimental results showed that the causticity of the LD on the stainless steel was significantly reduced and the wetted area was also increased.

Using additives to improve the thermal capacity of the LD and reduce its temperature increase in adiabatic dehumidifiers was also studied. Ren et al. [82] proposed a phase change enhanced desiccant solution using microencapsulated phase change materials to improve the dehumidification performance of LiCl desiccant solutions. The results showed that the thermal capacity of the new working solution was substantially increased in the melting range of the phase change material used and its vapour pressure was also decreased.

The above studies on the additives in LDs showed that adding surfactants to increase the wetted area of DRs can improve their HMT performance. However, the surfactants should be carefully selected as side effects such as foaming may occur, which will deteriorate the HMT performance. It is worthwhile to note that adding surfactants may change other properties of the LD besides the surface tension. Properties such as viscosity, thermal conductivity, and vapour pressure of the mixture should be measured and the influence of the properties on the performance of DRs should be further investigated. The previous studies [36, 78, 80] also showed that using nano-particles to enhance the thermal conductivity of LDs offered limited benefits to enhance the HMT performance of DRs. More research on new additives for LDs to improve HMT performance of DRs might be an area to be further investigated.

2.6 Other HMT improvement techniques

Several HMT improvement techniques that do not fall into the above categories are reviewed in this section. Kabeel [83] reported a new method for air dehumidification and desiccant regeneration. For the dehumidification, the humid air was injected into the LD stored in a tank and dehumidified through directly contacting with the LD. For the regeneration, the heated air with a temperature of 50-70 °C was injected into the LD tank to regenerate the LD. Mass transfer effectiveness of 0.87 and 0.92 was achieved during the dehumidification and regeneration processes, respectively. Gao et al. [84] proposed to use flash evaporation to regenerate LDs and experimentally investigated the influence of the concentration, environmental pressure under which the LD was regenerated, initial droplet temperature and diameter, and wall radiation on the superheat degree and the evaporation intensity. The results showed that the superheat degree and evaporation rate were significantly influenced by the environmental pressure and wall radiation, respectively. Yon et al. [85] developed a regenerator to concentrate LDs under vacuum conditions. The vacuum condition could reduce the boiling temperature of the LD and the boiling process was therefore achieved under relatively low temperatures. The LiBr water solutions were regenerated using hot water with a temperature of 36-40 °C under the vacuum pressures of 1000-2000 Pa, and it was shown that the mass fractions of LiBr increased by 0.07-0.09%. A cooling device with a cooling water temperature of 7-10 °C was used in the regenerator to condense the water from the air in the vacuum chamber. Yin et al. [86] proposed a pressurised LD dehumidifier in which the air was compressed before it was supplied to a packed-bed dehumidifier operating under a higher pressure of 0.2-0.5 MPa. The vapour pressure increased with the increase of the air pressure, providing a larger vapour pressure difference between the air and LD, as compared to the dehumidifiers operating under the atmospheric pressure. The experimental results showed that the outlet air humidity ratio of 0.9 g/kg was achieved when the air pressure was 0.5 MPa, which was much lower than those achieved under the atmospheric pressure.

Evaporative cooling, as presented in Fig. 4a), was also used to improve the HMT performance of ICDs with a flat plate configuration [87, 88]. The ICD investigated consisted of primary and secondary fluid channels which were arranged alternately, and one of them was for the primary air and LD and the other was for the secondary air and water. The LD and primary air were cooled by the evaporation of the water in the secondary fluid channel. An ICD using an outside evaporative cooling, as presented in Fig. 4b), was developed by Cheng et al. [89]. The LD was distributed on the inner surface of tubes with air flow inside. The outer surfaces of the tubes and fins were cooled by evaporative cooling. The experimental results showed that the MTR of this dehumidifier was substantially increased, compared to the same dehumidifier without using the outside evaporative cooling.

Fig. 4. ICDs using evaporative cooling (indicative and adapted from [87, 89]).

Ultrasonic atomisation is a technique using ultrasonic transducers to atomise the liquid into numerous liquid droplets with diameters of approximately 50 μm . It was used to increase the contact area between the air and LD in direct-contact DRs [90-92]. Yang et al. [91] developed an ultrasonic atomisation LD dehumidifier (UALDD) with a spray tower configuration, in which an ultrasonic transducer was used to generate high-frequency vibrations so that it can work as a spray nozzle. The LD was atomised into tiny droplets by the

ultrasonic transducer and sprayed into the dehumidifier due to gravity. The air flow was in the cross-flow configuration with the LD, while the real flow pattern of the air flow and the LD droplets sprayed in the tower was found to be parallel as the droplets were small and can be drifted by the air flow easily [91]. Compared to a cross-flow dehumidifier using the packing material, the desiccant consumption rate, which is the liquid-to-gas ratio times 1 kg/s of the UALDD was significantly decreased under the same dehumidification effectiveness. Yang et al. [92] further compared the performance of two LDC systems using packed-bed DRs and ultrasonic atomisation DRs, respectively. The results showed that the system power consumption reduced by 60.37%, 35.55%, and 41.66% for the low, medium and high load cases respectively, by using the ultrasonic atomisation DRs, in comparison with those using the packed-bed DRs. The ultrasonic atomisation can be considered as an effective technique to increase the mass transfer effectiveness of DRs. However, the carryover issue might be more severe when using UALDD due to the smaller size of liquid droplets. Yang et al. [90] claimed that the use of a mesh-type mist eliminator can capture 99% of the liquid droplets in the air flow. However, the high pressure drop resulted by the eliminator may also be a disadvantage.

A hyper-gravity liquid desiccant dehumidification system using rotating packed-bed DRs was recently proposed by Gu and Zhang [93]. The packing material in the rotating packed-bed DRs was rotated to create a strong artificial centrifugal force which could improve the HMT between the LD and air. The experimental results of a rotating packed-bed dehumidifier showed that the moisture transfer effectiveness of the dehumidifier with a rotating speed of 1000 r/min was higher than that of conventional packed-bed dehumidifiers while it was lower than that of the UALDD [90], under the same liquid-to-gas ratio.

3. HMT improvement techniques for indirect-contact DRs

HMT improvement techniques used for indirect-contact DRs mainly include using a third heat transfer fluid, selection of flow configurations, using inserts in fluid channels, tube arrangement, and mitigating membrane deflection.

3.1 Using a third heat transfer fluid

Abdel-Salam et al. [94] developed a three-fluid LAMEE using flat-sheet membranes, which was fabricated by deploying titanium tubes in the liquid channels of the LAMEE. The performance of the three-fluid LAMEE as an ICD was experimentally tested and the results showed that the moisture transfer effectiveness, sensible effectiveness, and total effectiveness were substantially improved by using cooling water, as compared to the three-fluid LAMEE without using cooling water. The performance of the same three-fluid LAMEE as an IHR was also tested by Abdel-Salam et al. [95], and the improvement in the regeneration performance was also achieved by using hot water. Huang et al. [96] investigated the influence of the cooling tube arrangement in the liquid channel on the heat transfer between the cooling fluid and the LD. The simulation results showed that the heat transfer between the LD and the cooling fluid was greatly influenced by the cooling tube arrangement. The optimal arrangement which maximises the Nusselt number (i.e. Nu) should be determined based on the Reynolds number (i.e. Re) of the LD. Isetti et al. [97] developed a three-fluid membrane contactor by replacing the fins of a plate-fin evaporator with hollow-fibre membranes. The LD was circulated among the plates while the air flowed inside the hollow-fibre membranes. The simulation results showed that the HMT of the three-fluid membrane contactor was improved by reducing the diameter of the hollow-fibre membranes while air-side pressure drop was also increased. Using a third heat transfer fluid may be considered as an effective technique to improve the HMT performance of indirect-contact DRs and cooling/heating tubes can be embedded in the fluid channels without taking extra space in the DRs. It may be worthwhile to further investigate the

design optimisation of indirect-contact ICDs and IHRs in order to develop compact DRs with high HMT performance.

3.2 Selection of flow configurations

The HMT effectiveness of flat-plate LAMEEs with a counter-flow configuration is generally higher than that with the parallel-flow and cross-flow configurations [94, 98]. However, a counter-flow or a parallel-flow LAMEE with adjacent inlet and outlet manifolds for the air and LD is impractical and the channel sealing between the neighbouring fluids is a critical issue [94, 99]. Therefore, most of the flat-plate LAMEEs were designed using the cross-flow configuration or counter-cross-flow configuration which is also known as the quasi-counter-flow configuration.

The counter-cross-flow configuration has been widely adopted in previous studies [98-100] and it was considered as a technique to improve the HMT performance of the LAMEE. A flat-plate LAMEE with a counter-cross-flow configuration (Fig. 5a) was developed by Moghaddam et al. [100]. Vali et al. [101] found that the effectiveness of the counter-cross-flow LAMEE was higher than the LAMEE with the cross-flow and was lower than the LAMEE with counter-flow. Zhang et al. [99] investigated the influence of the length-height ratio, length-width ratio, entry ratio, and flow configuration on the performance of a flat-plate LAMEE. The results from simulations showed that the mean Nu number and mean Sherwood number (i.e. Sh) of the air-side and liquid-side of the counter-cross-flow LAMEE were higher than those of the counter-flow LAMEE when the length-width ratio was close to one due to conjugate HMT and entrance effects caused by the counter-cross-flow configuration. A hexagonal flat-plate LAMEE (Fig. 5b) was developed by Huang et al. [102] in order to obtain the counter-cross-flow configuration. The influence of the channel height, inlet length ratio and air-side Re , as well as liquid-side Re on the HMT performance of the hexagonal flat-plate LAMEE was investigated. The simulation results showed that the air-side Nu and Sh were more

influenced by the channel height and air-side Re , while the liquid-side friction factor, Nu and Sh were substantially influenced by all the parameters investigated.

The counter-cross-flow configuration has been considered as an effective HMT improvement technique for flat-plate LAMEEs. The fabrication of LAMEEs using this configuration was relatively simple as compared to those using the counter-flow configuration. It is worthwhile to note that the investigation focusing on the influence of the flow configuration on the performance of indirect-contact ICDs and IHRs is limited, and further investigation on this topic may provide useful information for design optimisation of indirect-contact ICDs and IHRs.

Fig. 5. Counter-cross-flow configurations of flat-plate LAMEEs (adapted from [100, 102]).

For hollow-fibre LAMEEs, the cross-flow configuration [103, 104] and the counter-flow configuration [105, 106] have been widely used. The configuration used in [105, 106] was actually a counter-cross-flow configuration while it was considered as a counter-flow. The LAMEE with a parallel flow configuration was rarely reported due to its relatively low HMT effectiveness. Zhang et al. [103] compared the dehumidification performance of hollow-fibre LAMEEs with cross-flow and counter-flow configurations. Based on the simulation results, the air-side Nu and Sh with the cross-flow configuration were higher than those with the

counter-flow configuration when the air-side Re was above 35. Moreover, the cross-flow configuration has the advantages of low pressure drops and easy-to-seal as compared to the counter-flow configuration. The hollow-fibre LAMEE with a cross-flow configuration outperformed that with a counter-flow configuration in many aspects, and it has been widely used in LDC systems [107-109].

3.3 Using inserts in fluid channels

Inserts in fluid channels have been mainly used in flat-plate LAMEEs to enhance the convective HMT between the fluid flow and the membrane. The inserts can also serve as spacers to alleviate the membrane deflection resulted by the relatively high pressure on the liquid side against the air side [110]. Moghaddam et al. [12] developed an HMT improvement insert and deployed it in the air channel of a flat-plate LAMEE. This insert (Fig. 6a) consisted of ribs deployed along the air flow direction and rod-shape turbulators deployed perpendicular to the air flow direction. The experiments carried out by Oghabi [111] showed that the distance between the turbulators of the insert was more influential on the heat transfer performance than the distance between the ribs. The simulation results using the correlations developed based on the experimental results showed that the convective heat transfer coefficient in the air channel increased by 138% and the total effectiveness of the LAMEE improved by 11% when using the insert with an air-side Re of 1,570 [12]. A modified insert (Fig. 6b) was further developed by attaching a support grid to the membrane [94, 112]. The support grid was used to alleviate the deflection of the membrane. It may also enhance the convective HMT in the air channel while this enhancement effect was not investigated in [94, 112].

Fig. 6. Schematics of a) a turbulence-enhancing insert; and b) a similar insert with a support grid (adapted from [12, 112]).

A corrugated and pleated aluminium mesh was deployed in a flat-plate LAMEE with internal cooling to support the membrane from the air side [110]. Hout et al. [113] developed a desiccant dehumidification membrane ceiling, in which baffles were deployed in the liquid channel (see Fig. 7) to direct the flow of the desiccant to ensure that the LD can cover the membrane, and to reinforce the membrane and reduce deflection. Chen and Zhang [98] also used baffles in a hexagonal flat-plate LAMEE.

Fig. 7. LD dehumidification membrane ceiling with baffles (adapted from [113]).

The use of inserts in fluid channels of flat-plate LAMEEs has been investigated, while the application of this technique in hollow-fibre LAMEEs has not been found. The inserts have been proved as an effective technique to enhance the convective HMT and can also provide support for the membrane to alleviate its deflection. However, the inserts may also introduce

extra pressure drops which will increase parasitic energy consumption. The trade-off among the HMT enhancement, pressure drop, and the support effect can be potentially optimised via a multiphysics optimisation approach [114, 115]. The inserts could also be potentially applied to the LAMEE with internal cooling/heating to further improve its HMT performance.

3.4 Tube arrangement

Tube arrangement is considered as an important factor influencing the air-side HMT performance of hollow-fibre LAMEEs with a cross-flow configuration. Zhang et al. [104] compared the performance of hollow-fibre LAMEEs with the in-line and the staggered tube arrangements using computational fluid dynamics simulations. The results showed that the Nu and Sh on the air side of the LAMEE were substantially increased when using the staggered tube arrangement as compared to those of the in-line tube arrangement. The air-side friction factor (i.e. f_a) was also increased. The performance of hollow-fibre LAMEEs with the in-line and the staggered tube arrangements was further investigated by Ouyang and Zhang [116] by considering the effect of the skewed angle of the air flow on the tube bundle from 0° (i.e. parallel flow) to 90° (i.e. cross flow). Similar to the LAMEE with a cross-flow configuration, the HMT performance of the LAMEE with the skewed air flow using the staggered tube arrangement was always better than that using the in-line tube arrangement. The air-side friction factor was also increased. The results also showed that the average Nu , Sh , and f_a significantly increased with the increase of the skewed angle.

The HMT performance of the hollow-fibre LAMEE using the staggered tube arrangement was generally better than that using the in-line tube arrangement while the pressure drop was also higher for the staggered tube arrangement. The trade-off between the HMT improvement and the pressure drop needs to be further investigated and the tube arrangement needs to be optimally designed by considering overall system efficiency.

3.5 Mitigating membrane deflection

Membrane deflection in a flat-plate LAMEE may occur during the operation due to the significant pressure difference between the air flow and LD flow [117-119]. The membrane deflection will result in geometric variations of fluid channels and thus partially or fully block the air channels [118]. This will deteriorate the HMT performance and increase the air pressure drop [118, 120]. Meanwhile, flow maldistribution may occur due to the geometric variations of fluid channels [120]. Hemingson [121] presented that the sensible effectiveness, latent effectiveness, and total effectiveness of a round-around membrane energy exchanger which mainly consisted of two flat-plate LAMEEs, decreased by 15.6%, 10.7% and 12.5% respectively when the maximum membrane deflection was 10% of the undeformed air channel thickness. The techniques alleviating membrane deflections were therefore covered in this review as the HMT performance of DRs was directly influenced by the membrane deflection. For flat-plate LAMEEs, four methods and techniques including using membranes with high elastic modulus, membrane pre-stress, support grid and insert, and membrane support layer have been used to alleviate the membrane deflection and maintain the deflection below a design limit, and they are reviewed in this section. The deflection of the hollow-fibre membrane was also briefly reviewed in this section.

3.5.1 Membranes with high elastic modulus

Elastic modulus (E), which is the ratio of stress to strain in the elastic deformation region of a material, indicates the resistance of the material of being deformed elastically when it is subjected to certain stress. The extent of the membrane deflection will decrease with the increase of the elastic modulus. Therefore, it is recommended to select a membrane with a high value of elastic modulus for a LAMEE to alleviate the membrane deflection [117, 119]. Larson et al. [117] compared five measurement methods of membrane elastic modulus, including two tensile test methods and a bulge test [122] with three different analysis methods. It was stated that the bulge test with a secant analysis method was the most effective one. The secant method

was used to measure the elastic modulus of several membranes and the results can be found in [117, 119, 123].

3.5.2 Membrane pre-stress

Membrane pre-stress, which is a process of pulling the membrane tight before it is clamped down or glued to a fluid channel frame, has been considered as a technique to reduce membrane deflection. Larson et al. [117] investigated the influence of the membrane pre-stress and membrane pre-slack on the membrane deflection. The results showed that a large initial deflection in a low pressure range was resulted by the pre-slack of the membrane. The membrane deflection reduced by 15.72%, 8.78%, and 7.37% when the membrane was pre-stressed at a stress of 200 kPa and was applied to a pressure difference of 5, 10, and 15 kPa, respectively, as compared to the membrane without pre-stress or pre-slack. Maintenance of the pre-stress is also a significant factor influencing the long-term performance of pre-stressed membranes. Abdel-Salam et al. [94, 112] utilised a marine glue to seal the membrane onto the LD channel frame in an internally-cooled LAMEE after the membrane was well stretched. However, it was observed that there was an approximate 1.6 mm of deflection into air channels due to the drying of the liquid glue after a 70-hour consecutive operation as a dehumidifier. In order to avoid the pre-stress diminishing during the operation, double-sided adhesive tape was used to attach the membrane onto the LD channel frame [112]. The whole surface of the membrane had almost no bulging after around 165 hours of operation with the maximum LD temperature of 63 °C and a high pressure difference across the membrane.

3.5.3 Support grid and insert

A support grid can be placed on the low pressure side of the membrane which is generally the air side to provide good support for membranes in a flat-plate LAMEE and limit the membrane deflection [119]. Ge et al. [119] compared the deflections of a membrane with and without a support grid. It was found that the maximum membrane deflection was reduced from

4.6 mm to 2.0 mm at a pressure of 13,800 Pa when using a support grid with the opening size of 1 cm $\times$ 1 cm. Larson et al. [117] compared the deflection of a membrane using two different support grids with the opening sizes of 5.8 mm $\times$ 5.8 mm and 12.7 mm $\times$ 12.7 mm. It was found that the deflection of the membrane which was pre-stressed (1,230 kPa) and supported with the 12.7 mm grid, could be maintained below the design limit of 1 mm under the operating pressure. It was stated that the opening size of the support grid should be small enough to provide adequate mechanical support and also large enough to avoid a significant blockage of the HMT area of the membrane.

Spacers are generally used to maintain the space between the adjacent membranes of the air channel [124] and also used to further support the support grid [12, 94]. Moghaddam et al. [12] developed an insert consisting of ribs deployed along the air flow direction and rod-shape turbulators deployed perpendicular to the air flow direction, which was used as the spacer and the turbulence-enhancing insert. Abdel-Salam et al. [94] developed a support grid combined with an insert similar to that developed by Moghaddam et al. [12], which was used in the air channels of an internally-cooled LAMEE. The cooling tubes embedded in the LD channel were also supported by the ribs of the inserts in neighbouring air channels. The insert could also serve as a spacer to prevent the potential deformation of the support grid.

3.5.4 Support layer

A two-layer membrane, which consisted of an active layer using the porous membrane to transport water vapour and a support layer using non-woven fabric for example to enhance the elastic modulus of the membrane, can be used in the LAMEE to alleviate the membrane deflection [117, 119]. The support layer laminated onto the membrane is considered as a more convenient technique for manufacturing as compared to the external support grid [119]. Ge et al [119] found that the elastic modulus of a two-layer membrane increased approximately by six times as compared to the same membrane without the support layer. However, the vapour

diffusion resistance of the membrane increased from 12.9 to 29.5 s/m with the support layer. It was noteworthy that the elastic modulus of the two-layer membrane might be decreased by using the support layer as the original structure of the porous membrane might be damaged when a support layer was laminated onto it. The deflection of the two-layer membrane might still be alleviated as compared to the membrane without the support layer due to the increased thickness of the two-layer membranes.

3.5.5 Deflection of hollow-fibre membranes

During the fabrication of the hollow-fibre LAMEE, the cross-section shape of the fibre may be changed from a circle to an ellipse due to extrusion. The performance of hollow-fibre LAMEEs with elliptical fibres using counter-flow and cross-flow configurations were investigated by Huang et al. [125, 126]. The results in [125] showed that both the air side and the liquid side HMT performance of the counter-flow LAMEE deteriorated by the non-uniform temperature/concentration distribution on the cross section of the fluid channels due to the elliptical fibre. However, the results in [126] showed that the HMT performance of the cross-flow LAMEE was substantially enhanced by the elliptical fibre. The Nu and Sh for the air flow increased by 0.1%-36.9% and 0.1%-30.9% respectively and those for the liquid flow increased by 0.05-8.94% and 0.05%-8.28% respectively, when the ratio of the semi-minor axis to the semi-major axis decreased from 1.0 to 0.5 where the ratio of 1.0 stands for the circular cross-section shape. Huang et al. [127] investigated the influence of the curved hollow-fibre membrane in a cross-flow LAMEE. Compared to the LAMEE with straight hollow-fibre membranes, the air-side Nu of the LAMEE with the curved one decreased in the majority of the simulation cases when the air-side Re was in the range of 68.42-342.30, while the difference between the friction factors of these two types of LAMEEs was insignificant. Therefore, it was recommended that the mechanical strength of hollow-fibre membranes should be enhanced to keep the fibre straight [127].

3.6 Other HMT improvement techniques

The evaporative cooling was also used for internally-cooled LAMEEs to improve their HMT performance. Kozubal et al. [128] proposed a desiccant enhanced evaporating air conditioning device consisting of an internally-cooled LAMEE and a regenerative indirect evaporative cooler (RIEC), as presented in Fig. 8. The dry air from the LAMEE was supplied to the RIEC and the secondary air of the regenerative evaporative cooler was used as the secondary air in the LAMEE for evaporative cooling. The modelling results showed that the energy consumption of this device was reduced by 30%-90% as compared to a vapour compression system, dependent on the weather conditions. It was also suggested by Kozubal et al. [128] that this device could be separated into two individual components as an internally-cooled LAMEE with evaporative cooling using outdoor air as the secondary air and an RIEC. The performance of internally-cooled LAMEEs using evaporative cooling was also investigated by Woods and Kozubal [110, 129], and Huang et al. [130].

Fig. 8. A desiccant enhanced evaporating air conditioning (adapted from [128]).

The vacuum membrane distillation (VMD) was also used to improve the mass transfer performance of the distillation device for the LD regeneration [131, 132]. The distillate side of the VMD was continuously vacuumed by a vacuum pump and the vapour pressure of the distillate side was maintained at a relatively low level. The air with the water vapour from the

distillation device was first condensed using a cooling device and then exhausted to ambient by the vacuum pump. Zhou et al. [131] developed a solar VMD regenerator integrated with a photovoltaic thermal (PVT) collector. The LD was heated by the PVT and the vacuum pump was powered by the electricity generated from the PVT. A comparison of this solar VMD regenerator with a thermal regenerator was implemented using a mathematical model developed for solar VMD regenerators [131] and an analytical solution for direct-contact adiabatic DRs [133]. The results showed that the concentration of the LD from the VMD regenerator was higher than that from the thermal regenerator when the air temperature was lower than 32 °C, the air humidity ratio was above 19 g/kg, or the air mass flow rate was lower than 0.13 kg/s under the same operating conditions. A recent investigation [134] showed that the moisture transfer rate of the VMD regenerators could be 1.6-2.4 times and 4.5-6.0 times of the IHR and the adiabatic regenerator under the same LD inlet concentration, respectively. Although the VMD regenerator showed a promising regeneration performance, the overall performance of the LDC system using the VMD regenerator still needs to be evaluated by considering the electricity consumption of the vacuum pump and the cooling device used to condensate the water vapour.

4. Discussions

The applications, benefits and potential issues of the major HMT improvement techniques reviewed above are summarised in Table 4. Using a third heat transfer fluid has been widely applied to direct-contact and indirect-contact DRs, which can result in substantial performance improvements. However, using a third heat transfer fluid could also increase the complexity of the structure of DRs. Selection of flow configurations was also a technique applied to both direct-contact and indirect-contact DRs. The counter-flow configuration generally outperformed the cross-flow and parallel-flow configurations for the direct-contact DRs and

flat-plate LAMEEs in terms of HMT performance, while the cross-flow configuration was preferred for hollow-fibre LAMEEs.

From Table 4, it can be observed that the benefit of increasing the contact area between the LD and air could be achieved by three different techniques for direct-contact DRs, while the approaches to decreasing the vapour pressure and/or increasing the heat capacity of the LD are limited. Meanwhile, the additives which increase the thermal capacity and/or decrease the vapour pressure of LDs could also be used in indirect-contact DRs. The techniques developed for indirect-contact DRs mainly focused on increasing the air-side HMT coefficient, while they also increased air-side pressure drop. It is noted that the mechanisms of using packing materials and using inserts in fluid channels to increase the air-side HMT coefficient are similar and previous investigations on packing materials might be useful to assist in developing inserts for indirect-contact DRs. The tube arrangement has been used to improve the HMT performance of hollow-fibre LAMEEs, while this technique could also be applicable to direct-contact ICDs/IHRs with tube-bundle and finned-coil configurations. Mitigating membrane deflection is another important technique for indirect-contact DRs, which is also relevant to the design of inserts for HMT improvement. It is worthwhile to mention that multiple HMT improvement techniques could be used in DRs and the interactions among/between the techniques might influence the overall performance, which provides a wide range of research topics that could be investigated.

It can be also observed from Table 4 that the major mechanism of the HMT improvement techniques used for the direct-contact DR was to increase the contact area between LD and air, while that of the indirect-contact DR was to increase the air-side and liquid-side HMT coefficients. This could be explained by the fact that the distribution of the LD on the contact surface in the direct-contact DRs is mainly driven by gravity, and ensuring a decent surface wetting of the LD on the contact surface is a critical issue. The fluid flow of LD and air inside

indirect-contact DRs is confined by the membrane, and the wetting of the LD on the contact surface is easier to achieve in such DRs in comparison the direct-contact DRs. However, the use of membranes could increase the HMT resistance between the LD and air, which will negatively impact the overall HMT coefficient of LAMEEs.

Table 4. Characteristics of major heat and mass transfer improvement techniques.

Techniques	Applications	Benefits	Potential issues
Using a third heat transfer fluid	Direct-contact and indirect-contact DRs	<ul style="list-style-type: none"> • Increase the vapour pressure difference between LD and air. 	<ul style="list-style-type: none"> • Increase the complexity of the structure of DRs; • Heating/cooling of the third heat transfer fluid is required.
Selection of flow configurations	Direct-contact and indirect-contact DRs	<ul style="list-style-type: none"> • Increase the overall temperature and vapour pressure differences between LD and air; • Increase the air-side HMT coefficient of hollow-fibre membrane-based DRs. 	<ul style="list-style-type: none"> • Increase the complexity of the structure of DRs.
Packing materials	Direct-contact DRs	<ul style="list-style-type: none"> • Increase the contact area between LD and air; • Increase the air-side HMT coefficient. 	<ul style="list-style-type: none"> • Increase the air-side pressure drop.
Surface modification and surface materials	Direct-contact DRs	<ul style="list-style-type: none"> • Increase the contact area between LD and air; • Increase the durability of DRs. 	<ul style="list-style-type: none"> • Increase the cost of DRs; • Limited durability of coatings.
Adding additives in LDs	Direct-contact DRs	<ul style="list-style-type: none"> • Increase the contact area between LD and air; • Reduce the causticity of LDs; • Increase the thermal capacity of LDs; • Decrease the vapour pressure of LDs. 	<ul style="list-style-type: none"> • Increase the cost of LDs; • Result in foaming issues; • Increase pump power consumption.
Using inserts in fluid channels	Indirect-contact flat-plate DRs	<ul style="list-style-type: none"> • Increase air-side and/or liquid-side HMT coefficient; • Mitigate membrane deflection. 	<ul style="list-style-type: none"> • Increase air-side and/or liquid side pressure drop; • Increase the cost of DRs.
Tube arrangement	Indirect-contact hollow-fibre DRs	<ul style="list-style-type: none"> • Increase air-side HMT coefficient. 	<ul style="list-style-type: none"> • Increase the air-side pressure drop.
Mitigating membrane deflection	Indirect-contact DRs	<ul style="list-style-type: none"> • Increase HMT transfer area; • Alleviate flow maldistribution; • Reduce pressure drop. 	<ul style="list-style-type: none"> • Durability of the mitigation approach.

5. Conclusions

This paper provided an overview of the techniques used to improve the heat and mass transfer (HMT) performance of dehumidifiers and regenerators (DRs) used in liquid desiccant cooling systems. Some conclusive remarks are as follows.

- Packing materials have been widely used in direct-contact DRs. Such DRs are still expected to be the mainstream in the foreseeable future due to their simple structures.
- Additives in LDs and surface modifications of direct-contact DRs showed great potential to improve their HMT performance by increasing the contact area between the LD and air, reducing the causticity of LDs, increasing the heat capacity of LD, and/or decreasing the vapour pressure of LDs. However, additives in LDs may result in other issues such as liquid desiccant foaming and the stability of the additives in LDs should also be addressed.
- Carryover still remains a critical issue in direct-contact DRs. The flat-plate DRs with surface modification showed great potential to address this issue through forming a stable liquid film on the flat plate, and to increase the HMT area between LD and air.
- Using a third heat transfer fluid has been considered as an effective technique to improve the HMT performance of both direct-contact and indirect-contact DRs, while it will inevitably increase the complexity of the structure of DRs.
- Mitigating membrane deflection plays an essential role in indirect-contact DRs and it should be considered during the design phase of such DRs.
- Inserts used in the fluid channels of indirect-contact DRs have been proved to be an effective technique to enhance the HMT performance and could potentially mitigate the membrane deflection, while they also increase the air-side pressure drop.

6. Challenges and the future direction of research

Liquid desiccant cooling systems have been extensively investigated over the last several decades with limited success. However, they are now close to being viable and their economic

value proposition is now better than previously due to the development of new corrosion-resistant materials, improvements in HMT performance and the development of innovative solutions to mitigate the carryover of desiccant droplets. However, some challenges that are still faced and some recommendations for future work in this direction are as follows.

- One of the main challenges for packed-bed dehumidifiers and regenerators is to understand the HMT process between liquid desiccant and air due to their complex structures and potential existence of turbulent flow. The research in this field is still limited. The investigations are suggested to focus on the wettability of packing materials, air-side turbulence enhancement, and design optimisation of packing materials. Quantifying the wetting factor of liquid desiccants on packing materials might be also challenging while this could provide additional insights into the development of packing materials for dehumidifiers and regenerators.
- The influence of tube arrangement and design of fins on the performance of internally-cooled dehumidifiers and internally-heated regenerators with finned-coil configuration should be further investigated. The performance of fins with complex structures and surface modifications could be the main focus. Increasing the wetting factor of liquid desiccants on the fin surface might be the main challenge and this could be potentially solved by using hydrophilic coatings and micro/nano structured hydrophilic surfaces.
- Design optimisation of inserts is needed by considering the trade-off among the HMT improvement, pressure drop, and membrane deflection. This might be a challenging research topic as expert knowledge from multi-disciplines including solid mechanics, fluid mechanics, and HMT should be introduced simultaneously in this investigation. Multiphysics simulation tools may be useful for such investigations.

Further research is needed to develop strategies that can minimize or eliminate desiccant droplet carryover without compromising the HMT performance of the DRs.

- Further development of internally-cooled and internally-heated LAMEEs using hollow-fibre configuration is needed. Hollow-fibre LAMEEs with internal cooling/heating were rarely found in previous studies, although hollow-fibre LAMEEs have been widely investigated and applied to liquid desiccant cooling systems.
- The efforts should also focus on the development of low-cost and high durable coatings to improve surface wettability and contact area of direct-contact dehumidifiers and regenerators. The application of micro/nano structured hydrophilic surfaces is another aspect that is worthwhile to be investigated.
- Further research is needed to develop new additives to increase the thermal capacity and reduce vapour pressure of liquid desiccants, which could be applicable for both direct-contact and indirect contact dehumidifiers and regenerators. Achieving long-term stability of the additives in liquid desiccants might be a major challenge.

Declaration of interest

None.

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