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Abstract

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Characterisation and evaluation of a new phase change enhanced working solution for liquid desiccant cooling systems

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Abstract: Desiccant solutions play an essential role in desiccant cooling systems to absorb moisture from the process air. This paper presents the characterisation of a new working solution for liquid desiccant cooling systems. The new working solution was prepared through dispersion of micro-encapsulated phase change materials (MPCMs) into lithium chloride (LiCl) desiccant solutions to ensure that the dehumidification process was achieved under a low temperature condition and to improve thermal capacity and moisture removal efficiency of the mixture. The properties of the new solution, including density, enthalpy-temperature relationship, particle size distribution, thermal conductivity, and vapour pressure were characterised through either experimental tests or theoretical analysis. It was shown that the density and thermal conductivity of the new working solution slightly decreased with the increase of the mass fraction of the MPCMs in the mixture. The thermal capacity of the new working solution substantially increased in the melting temperature range of the MPCMs used. The vapour pressure of the new working solution decreased due to the existence of the MPCM particles. It is expected that the dehumidification efficiency of adiabatic dehumidifiers can be

22 potentially improved when using this new working solution due to the decreased vapour
23 pressure and increased thermal capacity of the PCM-LiCl desiccant solution.

24 **Keywords:** Desiccant cooling; phase change material; new working solution; characterisation;
25 vapour pressure.

26

27 **Nomenclature**

28 d diameter (m)

29 h enthalpy (J/kg)

30 k thermal conductivity (W/m K)

31 m mass (kg)

32 P vapour pressure (Pa)

33 t time (s)

34 T temperature (°C)

35 x_m mass fraction

36 x_v volume fraction

37

38 *Greek symbols*

39 α coefficient

40 α_R equivalent thermal conductivity depression

41 β coefficient

42 θ reduced temperature

43 π coefficient

44 ρ density (kg/m³)

45

46 *Subscripts*

47 a air

48 c core

49 e equivalent

50 $LiCl$ lithium chloride desiccant solution

51 PCM micro-encapsulated phase change material

52 $PCM-LiCl$ phase change enhanced LiCl desiccant solution

53 s shell

54

55 **1. Introduction**

56 Air conditioning is essential to our lives and is greatly impacting the quality of our life and
57 even saves lives during intense heat waves [1]. The amount of installed air conditioning systems
58 is expected to increase dramatically in the coming decades, largely driven by economic growth
59 and global warming [2]. Nowadays, the majority of air conditioning systems used were
60 developed based on the vapour compression cycle [3]. These systems can control sensible load
61 effectively but are very inefficient to deal with latent load, in particular under hot and humid
62 climatic conditions. This is because a significant amount of energy is required to dehumidify
63 the air by overcooling the air below its dew point temperature in order to remove the moisture

through condensation and then heating it to the desired temperature [4].

Liquid desiccant cooling as one of the alternative solutions has received increasing attention for air conditioning and dehumidification due to its effectiveness in humidity control and great potentials in energy savings [5-7]. A liquid desiccant is generally a concentrated salt solution such as lithium bromide (LiBr), lithium chloride (LiCl), and calcium chloride (CaCl_2) that directly absorbs moisture without cooling the air below its dew point. Liquid desiccant cooling can be driven by low-grade thermal energy (50-90 °C) such as waste heat or solar energy [8]. As the building peak cooling demand generally occurs at approximately the same time as local peak solar radiation, this opens up opportunities of using solar energy to drive liquid desiccant cooling and even to take air conditioning off the grid with the assistance of thermal energy storage systems.

Various types of liquid desiccant cooling systems and their potentials to maintain acceptable indoor thermal comfort under different climatic conditions have been studied. Ham et al. [9], for instance, developed a liquid desiccant and dew point evaporative cooling assisted 100% outdoor air system. The simulation results showed that 12% of the primary energy can be saved by using this system, in comparison with a typical variable air volume system. Elmer et al. [10] developed a liquid desiccant cooling system consisting of a regenerator, a dehumidifier and an evaporative inter-cooler integrated with an energy exchanger. The experimental results showed that the dehumidification effectiveness of this system was 30-47% with an average electrical COP of 2.5. Chen et al. [11] proposed a liquid desiccant dehumidifier and a regenerative indirect evaporative cooling system for fresh air treatment. The thermal

energy obtained from solar collectors was used for liquid desiccant regeneration. The results showed that the energy saving of this system was 22.4-53.2% under various inlet air conditions, in comparison to a conventional chilled water air conditioning system. A solar driven liquid desiccant cooling system was developed by a company named L-DCS Technology [12]. This system was installed in a building in Singapore and used for cooling and dehumidification [13].

A dehumidifier is a key component in a liquid desiccant cooling system. Adiabatic dehumidifiers are relatively simple units, but they must work with a high desiccant flow rate and a high air flow rate in order to achieve a better dehumidification efficiency [6, 14]. In adiabatic dehumidifiers, the temperature of the desiccant solution continuously increases along the desiccant flow direction. The increase in the solution temperature deteriorates the dehumidification efficiency as the ability of a desiccant solution to attract water vapour from an air stream decreases with the increase of the solution temperature and the decrease of the solution concentration [15]. In order to ensure dehumidifiers work with high efficiency and minimise the carryover of desiccant droplets, internally cooled dehumidifiers which can allow the desiccant solution working in a low temperature and low flow rate condition were studied [16]. The performance comparison of an adiabatic dehumidifier with an internally cooled dehumidifier showed that the dehumidification effectiveness of the internally cooled dehumidifier was improved from 0.3876 - 0.4771 to 0.4769 - 0.7058, in comparison to that of the adiabatic dehumidifier [17]. However, the inherent complex configuration of the internally cooled dehumidifiers and high maintenance costs make these systems less attractive.

Phase change materials (PCMs) with an ability to provide high energy storage densities and

the characteristics to store thermal energy at relatively constant temperatures have attracted wide attention for developing high-performance buildings [18, 19]. The development of PCMs and PCM thermal energy storage for liquid desiccant cooling systems have been reported in a few studies [20-22]. Niu et al. [20], for instance, proposed to use micro-nanoencapsulated PCMs as a heat transfer fluid to improve the performance of internally cooled dehumidifiers in liquid desiccant cooling systems. The micro-nanoencapsulated PCMs were prepared and their thermo-physical properties were characterised. However, the real application of such materials in dehumidifiers was not reported. Al-Abidi et al. [21] and Mahdi and Nsofor [22] respectively developed a triplex tube PCM thermal energy storage for liquid desiccant cooling systems. Al-Abidi et al. [21] experimentally tested the charging performance of the PCM thermal storage unit using a paraffin wax with a melting temperature of 82 °C while Mahdi and Nsofor [22] numerically investigated the charging performance of the thermal energy storage using the same paraffin wax but was enhanced by alumina nanoparticles and a porous copper foam. However, both studies did not integrate the PCM thermal energy storage into liquid desiccant cooling systems.

In this study, a novel phase change enhanced LiCl (i.e. PCM-LiCl) desiccant solution was proposed to improve the dehumidification efficiency of adiabatic dehumidifiers. The new solution was prepared by dispersing micro-encapsulated PCMs (MPCMs) into LiCl desiccant solutions. As MPCMs have a relatively large thermal storage capacity, the dispersion of MPCMs into liquid desiccant solutions can ensure the mixture work under a low temperature condition, improving overall dehumidification efficiency. The properties of the new PCM-LiCl

desiccant solution such as density, enthalpy-temperature (h - T) relationship, particle size distribution, thermal conductivity, and vapour pressure were characterised through either experimental measurements or theoretical investigation.

2. Development and characterisation of PCM-LiCl desiccant solutions

Dehumidifiers can generally offer a better performance when the desiccant solution is working in a low temperature condition such as in the range of 20-30 °C [23-24]. As shown in Fig. 1a [25], the temperature of the LiCl desiccant solution is continuously increased along the height of the adiabatic dehumidifier due to the heat and mass transfer between the process air and the liquid desiccant and the absorption heat released during the dehumidification process. This increased temperature will lead to the increase in the vapour pressure of the liquid desiccant and therefore decrease the vapour pressure difference between the process air and liquid desiccant, which deteriorates the moisture transfer and dehumidification effectiveness of the adiabatic dehumidifier. This deterioration can be further confirmed by the results (see Fig. 1b) reported in another study [26], in which it was shown that the mass flux of moisture between the process air and liquid desiccant decreased along the flow direction of the liquid desiccant. As PCMs have a large storage density, the dispersion of MPCMs into liquid desiccants can improve the thermal capacity of the mixture and therefore can decrease the temperature increase of the liquid desiccant along the flow direction of the adiabatic dehumidifier, improving overall dehumidification effectiveness.

a) Temperature of the liquid desiccant [25]

b) Mass flux of moisture [26]

Fig. 1. Temperature of LiCl liquid desiccant and mass flux of moisture along the flow direction of an adiabatic dehumidifier.

In this study, two commercially available MPCM products, i.e. BASF Micronal DS 5038X and Micronal DS 5040X with a melting temperature of 25 °C and 23 °C respectively, were used to prepare phase change enhanced LiCl desiccant solutions. Both MPCMs were made of a highly crosslinked polymethylmethacrylate (PMMA) polymer wall and paraffin inside as the PCM. It is noted that the MPCMs used in this study might not be optimal. As the temperature of the inlet working solution of the dehumidifier is a controlled variable, the phase change materials should be selected based on the set-point of the inlet working solution temperature in order to ensure that the PCM undergoes the phase change process during the dehumidification.

Deionized water and LiCl with a purity higher than 98% were used to prepare LiCl desiccant solutions. The PCM-LiCl desiccant solution was prepared through directly dispersing the MPCM particles into the LiCl desiccant solution via mechanical stirring.

2.1 Characterisation of PCM-LiCl desiccant solutions

To understand the likely benefits of using this new working solution for air dehumidification, the properties of the PCM-LiCl desiccant solutions, including density, h - T relationship, particle size distribution, thermal conductivity, and vapour pressure should be first characterised. In this study, these properties were characterised through either theoretical analysis or experimental measurements.

2.1.1 Density

The density of the PCM-LiCl desiccant solution was determined based on the density of each insoluble component of the mixture as the potential non-homogeneity of the new solution might introduce errors in measurements of the mixture. As the PMMA has good resistance to LiCl and is insoluble in LiCl desiccant solutions, the density of the PCM-LiCl desiccant solution can be calculated using Eq. (1) [27], in which the density of the MPCM was measured using a pycnometer (to be introduced in Section 2.2) and the density of the LiCl desiccant solution was determined using the correlation expressed in Eq. (2) [28].

$$\rho_{PCM-LiCl} = \frac{\rho_{PCM}\rho_{LiCl}}{\rho_{PCM}(1-x_{m,PCM}) + \rho_{LiCl}x_{m,PCM}} \quad (1)$$

$$\rho_{LiCl} = \rho_{H2O} \sum_{i=0}^3 \alpha_i \left(\frac{x_{m,LiCl}}{1-x_{m,LiCl}} \right)^i \quad (2)$$

where ρ is the density, α_i are the parameters and the values of α_0 – α_3 were 1.0, 0.540966, -0.303792, 0.100791, respectively [28], x_m is the mass fraction, and the subscripts $PCM-LiCl$,

PCM and *LiCl* indicate phase change enhanced LiCl desiccant solution, micro-encapsulated phase change material, and LiCl desiccant solution, respectively.

2.1.2 Enthalpy-temperature (h - T) relationship

Differential scanning calorimeter (DSC) tests are commonly used to measure h - T relationships of PCMs. In this study, the h - T relationship of the PCM-LiCl desiccant solution was not measured directly as LiCl desiccant solutions may corrode the metal container of the DSC device and further damage the equipment. Thus, the h - T relationship of the new solution was determined using Eq. (3), based on the enthalpy of the LiCl desiccant solution determined using Eq. (4) [29] and the DSC test results of the MPCMs.

$$h_{PCM-LiCl} = x_{m,PCM} h_{PCM} + (1 - x_{m,PCM}) h_{LiCl} \quad (3)$$

$$h_{LiCl} = A + BT + CT^2 \quad (4)$$

where h is the enthalpy, T is the temperature, and the coefficients of A , B , and C are calculated using Eqs. (5-7) [29], respectively.

$$A = -66.2324 + 11.2711x_{m,LiCl} - 0.79853x_{m,LiCl}^2 + (2.1534E-02)x_{m,LiCl}^3 - (1.66352E-04)x_{m,LiCl}^4 \quad (5)$$

$$B = 4.5751 - 0.146924x_{m,LiCl} + (6.307226E-03)x_{m,LiCl}^2 - (1.38054E-04)x_{m,LiCl}^3 + (1.06690E-06)x_{m,LiCl}^4 \quad (6)$$

$$C = (-8.09689E-04) + (2.18145E-04)x_{m,LiCl} - (1.36194E-05)x_{m,LiCl}^2 + (3.20998E-07)x_{m,LiCl}^3 - (2.64266E-09)x_{m,LiCl}^4 \quad (7)$$

2.1.3 Thermal conductivity

The thermal conductivity of the PCM-LiCl desiccant solution was calculated using

Maxwell's equation as shown in Eq. (8), which has been widely used to calculate the thermal conductivity of MPCM suspensions [27, 30]. The thermal conductivity of the MPCM particles (k_{PCM}) was determined using the composite sphere approach reported by Goel et al. [30], in which the heat transfer resistance of the shell material was determined based on the thickness of the MPCM shell. The heat transfer resistance of the core material was evaluated based on the assumption that a solid sphere is in an infinite medium [31]. The thermal conductivity of the MPCM can then be calculated using Eq. (9) [30]. The diameter of the MPCM particle was measured using a particle size analyser to be introduced in Section 2.2 and the thickness of the PMMA shell was determined using the composition of the MPCM measured using a thermogravimetric analyser (see Section 2.2). The thermal conductivity of the LiCl desiccant solution is calculated using Eq. (10) [28].

$$\frac{k_{PCM-LiCl}}{k_{LiCl}} = \frac{2k_{LiCl} + k_{PCM} + 2x_{v,PCM}(k_{PCM} - k_{LiCl})}{2k_{LiCl} + k_{PCM} - x_{v,PCM}(k_{PCM} - k_{LiCl})} \quad (8)$$

$$\frac{1}{k_{PCM}d_{PCM}} = \frac{1}{k_c d_c} + \frac{d_{PCM} - d_c}{k_s d_{PCM} d_c} \quad (9)$$

$$k_{LiCl} = k_{H2O} - \alpha_R x_{m,LiCl,e} \quad (10)$$

where k is the thermal conductivity, x_v is the volume fraction, d is the diameter, α_R is the equivalent thermal conductivity depression, $x_{m,LiCl,e}$ is the equivalent ionic concentration, and the subscripts s and c indicate shell and core, respectively.

2.1.4 Vapour pressure

The dehumidification performance of a liquid desiccant is directly influenced by the vapour pressure difference between the liquid desiccant and process air [5]. In this study, the vapour pressure of the PCM-LiCl desiccant solution was measured using a thermogravimetric method

[32]. In this method, the mass loss of the sample is measured using a thermogravimetric analyser (i.e. TGA 5500 from TA Instruments was used in this study) and the result is then used to determine the vapour pressure of the solution by using the Langmuir equation for free vaporisation, as shown in Eq. (11) [33].

$$\log(P_T) = \beta_1 \log\left(\frac{1}{\beta_2} \left|\frac{dm}{dt}\right|_T\right) + \beta_3 \quad (11)$$

where $\left|\frac{dm}{dt}\right|_T$ and P_T are the mass loss rate and the vapour pressure at a given temperature respectively, and β_1 , β_2 and β_3 are the coefficients influenced by the geometry structure of the crucible. In this study, these three coefficients were determined based on the experimental results for a reference substance (i.e. pure water) with the known vapour pressure.

During the test, the sample was placed in a sealed crucible with a 0.35 mm-diameter hole on the lid, as illustrated in Fig. 2a. The crucible was then placed on the holder of the balance inside the thermogravimetric analyser (Fig. 2b). The sample was purged by a pure nitrogen gas flow in order to maintain the water content outside the crucible close to zero.

a) Schematic of vapour pressure measurement

b) Thermogravimetric analyser used in this study

Fig. 2. Vapour pressure measurement using a thermogravimetric analyser.

2.2 Characterisation of MPCMs and pure LiCl desiccant solutions

The properties of the MPCMs were determined either using the information provided in the product data sheet [34] or through the experimental measurements.

The MPCM used was in a physical form of powder and the bulk density of the MPCM was provided in the datasheet [34]. However, the particle density of the MPCM was required to determine the density of the PCM-LiCl desiccant solutions. In this study, a pycnometer was used to measure the particle density of the MPCM.

DSC tests were carried out to characterise the h - T relationship of the two MPCMs. The tests were implemented using a micro DSC (micro DSC III, SETARAM) device with a weight of the samples of around 300 mg. The heating/cooling rate used was 0.05 K/min.

The particle size distribution of the MPCM was measured using a laser diffraction particle size analyser and the sample was pre-processed in an ultrasonic bath for deagglomeration of the particles before the measurement. The results were analyzed using Mie model [35], which worked well for homogeneous and spherical particles with a diameter less than 30 μm [36, 37]. The Mie model was derived by solving Maxwell's equations describing electromagnetic

radiation for the light scattered by a homogeneous sphere under the uniform illumination [35].

Thermogravimetric analysis was carried out using a thermogravimetric analyser to determine the composition of the MPCMs, and then to calculate the thickness of the PMMA shell. During the test, the MPCM was heated to a temperature of 600 °C with a scanning rate of 1.0 K/min, and the test was then carried out using a nitrogen gas flow.

As LiCl is highly hygroscopic and pure LiCl may absorb the moisture from the air during the preparation. A thermogravimetric analysis test for LiCl desiccant solutions was therefore carried out to determine the mass fraction of LiCl in the solution. During the measurement, the LiCl desiccant solution was heated to a temperature of 350 °C with a scanning rate of 5.0 K/min and was then maintained at 350 °C for 18 hours [38]. The thermogravimetric analysis test was also performed with a nitrogen gas flow.

3. Results of properties characterisation

In this section, the properties of the MPCMs and PCM-LiCl desiccant solutions were respectively characterised using the methods introduced in Section 2. The majority of the tests presented in this study were repeated in order to confirm the consistency of the results.

3.1 Results of characterisation of MPCM properties

The measured densities of the MPCM DS 5038X and MPCM DS 5040X were 990.9 ± 0.6 kg/m³ and 1012.6 ± 0.4 kg/m³, respectively. These results were considered to be reasonable as the density of the two major compositions, i.e. paraffin wax and PMMA, were around 850 kg m⁻³ and 1150 kg m⁻³, respectively.

The DSC curves of the MPCM DS 5038X and MPCM DS 5040X are presented in Fig. 3

and their onset temperatures, peak temperatures, and heat of fusion during the cooling and heating processes are summarized in Table 1. The heat of fusion of the MPCM was calculated based on the temperature range of 15-28 °C. It can be observed that the peak phase change temperatures of the MPCM DS 5038X for both heating and cooling were slightly higher than those of the MPCM DS 5040X. The results from Table 1 also showed that the onset temperatures of the MPCM DS 5038X were higher than those of the MPCM DS 5040X during both cooling and heating processes.

Table 1. Onset temperatures, peak temperatures, and heat of fusion of the two MPCMs.

	DS 5038X			DS 5040X		
	Onset Temp. (°C)	Peak Temp.(°C)	Heat of fusion (J/g)	Onset Temp. (°C)	Peak Temp. (°C)	Heat of fusion (J/g)
Heating	22.55	25.37	96.7	19.87	24.64	94.8
Cooling	24.37	22.60	96.2	23.83	21.53	93.2

Fig. 3. DSC test results of DS 5038X and DS 5040X.

The measured particle size distributions of the MPCMs are presented in Fig. 4. The volumetric average diameters of the MPCMs DS 5038X and DS 5040X were determined as 3.51 μm and 3.68 μm , respectively. It can be observed that the particle size distributions of both MPCMs were in the range of 1 - 10 μm .

a) DS 5038X

b) DS 5040X

Fig. 4. Particle size distribution of the two MPCMs.

The results (i.e. percentage weight and mass loss rate of the sample) from the thermogravimetric analysis of the MPCMs DS 5038X and DS 5040X and a sample of the MPCM DS 5038X after the decomposition test are presented in Fig. 5. The thermogravimetric analysis results of the shell material (i.e. PMMA) obtained from [39] were also provided. It can be seen that the thermal degradation of the MPCM DS 5038X can be divided into three phases and the MPCM was mainly decomposed in the first two phases at a temperature below 330 °C, and the PMMA was completely decomposed at a temperature of around 454 °C (Fig. 5a). Similar trends were also observed for the MPCM DS 5040X (Fig. 5b). By comparing the thermogravimetric analysis curve of the MPCM to that of the PMMA, it can be derived that the

composition of the MPCM DS 5038X was 17.4% wt. PMMA, 67.5% wt. paraffin, and 15.1% wt. residual and that of the MPCM DS 5040X was 17.1% wt. PMMA, 69.5% wt. paraffin, and 13.4% wt. residual. The similar results were also reported in [37, 40].

a) DS 5038X

b) DS 5040X

c) DS 5038X after the decomposition test

Fig. 5. Decomposition of PMMA [39], MPCM DS 5038X and MPCM DS 5040X.

3.2 Results of characterisation of PCM-LiCl desiccant solutions

3.2.1 Verification of vapour pressure measurement

The vapour pressure of the LiCl desiccant solution was measured using the

thermogravimetric method and the results were compared with the calculated values determined using the correlation expressed in Eq. (12) [28]. The concentration of the LiCl desiccant solution was first determined via a thermogravimetric analysis test and the vapour pressure of the LiCl desiccant solution was then measured at a temperature of 50 °C using the method presented in Fig. 2. The test results are presented in Fig. 6, which were measured based on the initial concentration of the LiCl solution of 29.53%. It can be found that the vapour pressure of the solution decreased with the increase of the solution concentration and the measured values generally agreed well with the calculated results. The average and maximum deviations between the measured and calculated values were 1.9% and 5.5%, respectively. It is worthwhile to note that the total mass of the test sample used was relatively small due to the capacity of the crucible used and the increase of the concentration was resulted by the continuous loss of the water in the solution.

$$P_{LiCl} = \pi_{25} f(x_{m,LiCl}, \theta) P_{H_2O} \quad (12)$$

where θ is the reduced temperature, $f(x_{m,LiCl}, \theta)$ is determined using Eq. (13) [28], and π_{25} is calculated using Eq. (14) [28].

$$f(x_{m,LiCl}, \theta) = 2 - \left[1 + \left(\frac{x_{m,LiCl}}{\pi_0} \right)^{\pi_1} \right]^{\pi_2} + \left\{ \left[1 + \left(\frac{x_{m,LiCl}}{\pi_3} \right)^{\pi_4} \right]^{\pi_5} - 1 \right\} \theta \quad (13)$$

$$\pi_{25} = 1 - \left[1 + \left(\frac{x_{m,LiCl}}{\pi_6} \right)^{\pi_7} \right]^{\pi_8} - \pi_9 \exp \left(- \frac{(x_{m,LiCl} - 0.1)^2}{0.005} \right) \quad (14)$$

where π_0 - π_8 are the coefficients and the values used were provided in Table 2 [28].

Fig. 6. Measured and calculated vapour pressures of the LiCl desiccant solution.

Table 2. Coefficients for vapour pressure calculation of LiCl desiccant solutions [28].

π_0	π_1	π_2	π_3	π_4	π_5	π_6	π_7	π_8	π_9
0.28	4.30	0.60	0.21	5.10	0.49	0.362	-4.75	-0.40	0.03

3.2.2 Properties characterisation

In this study, the LiCl desiccant solution with a concentration of 35% was first prepared and the MPCMs with different mass fractions were then mixed with the LiCl desiccant solution to prepare the PCM-LiCl desiccant solutions. The densities of different PCM-LiCl desiccant solutions were then calculated using Eqs. (1) and (2) and the results are presented in Fig. 7. It can be seen that the density of the PCM-LiCl desiccant solutions decreased with the increase of the mass fraction of the MPCMs as the density of the MPCMs was lower than that of the LiCl desiccant solution. The density of the mixture using the MPCM DS 5038X was always lower than that using the MPCM DS 5040X which was resulted by the relatively low density of the MPCM DS 5038X. It is noted that the density of the mixture calculated using Eq. (1) [27]

is applicable to homogenous fluids and the PCM-LiCl desiccant solution developed in this study can be considered as homogenous when it is well mixed.

Fig. 7. Density of the PCM-LiCl desiccant solution.

The h - T relationship of the PCM-LiCl desiccant solutions was determined using Eqs. (3) and (4). The heating curve of the MPCM obtained from the DSC measurement was used to evaluate the enthalpy of the MPCM. The results are presented in Fig. 8. The enthalpy of the LiCl desiccant solution without MPCMs was also presented in this figure. It can be observed that the enthalpy of the PCM-LiCl desiccant solution increased with the increase of the solution temperature and the mass fraction of the MPCMs in the mixture. A large increasing rate occurred in the MPCM melting temperature range of 20-27 °C. The enthalpy of the solution then increased almost linearly if further increasing the solution temperature. There was not a clear difference between the use of two different MPCMs.

a) DS 5038X

b) DS 5040X

Fig. 8. Enthalpy-temperature relationships of the pure LiCl desiccant solution and PCM-LiCl desiccant solutions with different mass fractions of the MPCMs.

The thermal conductivity of the PCM-LiCl desiccant solution was calculated using Eqs. (8) and (9) based on the composition and particle size of the MPCM determined. It is noted that the diameter of the particles dispersed into the LiCl desiccant solution was assumed to be the same as the volumetric average diameter of the particles. It was also assumed that the residual of the MPCMs obtained from the thermogravimetric analysis had the same thermal conductivity

as the PCM used. The resulted thermal conductivity of the PCM-LiCl desiccant solutions is presented in Fig. 9. It can be observed that the thermal conductivities of the PCM-LiCl desiccant solutions using the MPCM DS 5040X and DS 5038X were very close to each other when the mass fraction of the MPCMs was less than 20%. The thermal conductivity of the PCM-LiCl desiccant solutions decreased with the increase of the mass fraction of the MPCMs as the thermal conductivity of the MPCM particle was lower than that of the LiCl desiccant solution.

Fig. 9. Thermal conductivity of the PCM-LiCl desiccant solutions with different mass fractions of MPCMs.

The vapour pressures of the PCM-LiCl desiccant solutions with different mass fractions of the two MPCMs were measured using the thermogravimetric method. As the variation in the vapour pressures of the PCM-LiCl solutions using the two MPCMs showed a similar trend, the results of the PCM-LiCl solution using the MPCM DS 5040X under the temperature of 50 °C were presented only.

During the measurement, the LiCl desiccant solution was first prepared and the concentration of the LiCl desiccant solution was determined via a thermogravimetric analysis test. A relatively low initial concentration of the LiCl desiccant solution (i.e. 29.53%) was used

to prepare PCM-LiCl desiccant solutions as the concentration of the desiccant solution was expected to increase during the vapour pressure measurement due to continuous loss of the water in the solution. The PCM-LiCl desiccant solution was then prepared in the crucible presented in Fig. 2a. Table 3 summarises the details of the three samples used in the test. It is worthwhile to note that the mass fraction of the MPCM in each test sample cannot be precisely controlled during the preparation.

Table 3. Test samples prepared for vapour pressure measurement.

Test sample	Weight (mg)	Mass fraction of the MPCM	Mass fraction of the LiCl
Sample 1	49.158	0.029	0.288
Sample 2	57.424	0.128	0.258
Sample 3	54.190	0.180	0.243

The measurement results of the PCM-LiCl desiccant solution using the MPCM DS 5040X under the temperature of 50 °C are presented in Figs. 10 and 11. The vapour pressures of LiCl desiccant solutions without the MPCM were also presented, which were calculated based on the same temperature condition and the same initial mass fractions of LiCl in the desiccant solutions as those presented in Table 3. The vapour pressure of the pure LiCl desiccant solution was determined using Eqs. (12)-(14). It can be seen that the vapour pressures of the PCM-LiCl desiccant solutions of three samples continuously decreased as a function of time. This is because the mass fractions of both MPCM and LiCl continuously increased with time during the test due to the water loss (Fig. 11). For each test sample, the vapour pressure of the PCM-LiCl desiccant solution was always lower than that of the pure LiCl desiccant solution during

the test period due to the existence of the MPCM particles. The vapour pressure of the PCM-LiCl desiccant solution decreased with the increase of the mass fraction of the MPCM in the mixture.

Fig. 10. Variation of vapour pressure of the PCM-LiCl desiccant solutions and pure LiCl desiccant solutions as a function of time.

Fig. 11. Variation of mass fractions of the MPCM and LiCl in the PCM-LiCl desiccant solutions as a function of time.

From the above results, it can be concluded that the dispersion of MPCMs into the liquid

desiccant solution can decrease the vapour pressure and increase the thermal capacity of the mixture, which can improve the dehumidification efficiency of adiabatic dehumidifiers although the thermal conductivity of the mixture was slightly decreased. In principle, a low solution flow rate can be used in the liquid desiccant cooling system when using the PCM-LiCl desiccant solution due to the increased thermal capacity and reduced vapour pressure. It is also expected that the size of the dehumidifier using the new working solution can be decreased without compromising the dehumidification performance, when compared to the dehumidifier using pure desiccant solutions. In addition, the temperature of the inlet solution to the dehumidifier should be optimised in order to maximise the benefits of using MPCMs in the desiccant solution. It is also noteworthy that thermal regeneration might not be an optimal method for liquid desiccant cooling systems when using PCM-LiCl desiccant solutions and non-thermal regeneration methods may be required, which will be investigated in future studies. However, the potential benefits of using PCM-LiCl desiccant solutions should be evaluated in liquid desiccant cooling systems by considering the influence of the MPCM particles in both dehumidifiers and regenerators. Adding the MPCM particles into liquid desiccant solutions may increase the power consumptions of the circulation pump. Meanwhile, the mass fraction of the MPCMs in the mixture should be optimised. The long-term performance and potential segregation of MPCM particles in the new working solution should also be examined.

4. Conclusions

This study presented the development and characterisation of a new phase change enhanced working solution for liquid desiccant cooling systems. The new solution was prepared through

dispersion of micro-encapsulated PCMs (i.e. Micronal DS 5038X and DS 5040X) into the base fluid of the LiCl desiccant solution. The properties including density, h - T relationship, thermal conductivity, particle size distribution, and vapour pressure of the new solution were characterised either through direct measurement or theoretical analysis.

The results showed that the density of the phase change enhanced LiCl (PCM-LiCl) desiccant solution decreased with the increase of the mass fraction of the MPCMs in the mixture due to the lower density of the MPCMs used in comparison with the pure LiCl solutions. The thermal capacity of the PCM-LiCl desiccant solutions was substantially increased in the melting range of the MPCMs. The thermal conductivities of the PCM-LiCl desiccant solutions using the MPCMs DS 5038X and DS 5040X were very close to each other when the mass fraction of the MPCMs was less than 20% and the thermal conductivity decreased with the increase of the mass fraction of the MPCMs. The vapour pressure of the new working solution decreased due to the existence of the MPCM particle as compared to the LiCl solution without using the MPCMs. The dehumidification performance of adiabatic dehumidifiers could be potentially improved by using this new working solution due to its decreased vapour pressure and increased thermal capacity, which will be investigated in our future studies.

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