

EXPERIMENTAL PERFORMANCE INVESTIGATION OF SUPERABSORBENT POLYMER AND POTASSIUM FORMATE COATED HEAT EXCHANGERS

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ABSTRACT

The efficiency of the air conditioning process can be improved by employing desiccant coated heat exchangers (DCHEs). Currently, DCHE's performance is not sufficiently high due to the restricted sorption capacity, high regeneration temperature, and long term corrosive effect of the selected desiccating material. In this study, we have developed a composite desiccant by combining a hydrophilic superabsorbent polymer and a less corrosive potassium formate salt. Due to high absorption capacity and excellent water retention ability, the composite polymer demonstrated 4-8 times gain in the sorption capacity when compared with pure/composite silica gel. Further, it recorded two times improvement in dehumidification capacity and energy efficiency when coated on a heat exchanger as opposed to only 20-30% improvement in the case of composite silica gel with potassium formate salt. Lastly, the composite polymer desiccant could operate 2-4 times longer than silica gel coated heat exchangers.

Keywords: experiments; sorption; desiccant coated heat exchangers; superabsorbent polymer; potassium formate; dehumidification

NONMENCLATURE

C_p	specific heat capacity at constant pressure, kJ/kgK
h	specific enthalpy
\dot{m}_a	mass flow rate, kg/s or kg/h
t	time, s or min
T	temperature, °C or K
ω	humidity ratio, g/kg
<i>Subscripts</i>	
a	air
cyc	cycle
hw	hot water

in	inlet
out	outlet
<i>Abbreviations</i>	
COP _{th}	thermal coefficient of performance
CPCHE	composite polymer coated heat exchanger
DCHE	desiccant coated heat exchanger
MRC	moisture removal capacity
SGCHE	silica gel coated heat exchanger

1. INTRODUCTION

The simultaneous handling of sensible and latent cooling loads has resulted in the poor energy efficiency of the hitherto vapor compression air-conditioning systems. Desiccant coated heat exchangers (DCHEs) decouple sensible and latent cooling loads and improve the effectiveness of the air-conditioning process. The selection of a desiccant with high sorption capacity, fast kinetics, appropriate stability, and low regeneration temperature has been the key to achieve improved dehumidification performance [1].

Pure solid desiccants namely silica gel, zeolite, and molecular sieves have low adsorption capacity due to limitations in their pore characteristics [2]. Hygroscopic salts such as lithium chloride (LiCl) and calcium chloride (CaCl₂) have been combined with these adsorbents in appropriate proportions due to their high absorbability and stability [3]. Although higher salt concentration in the composite solid desiccant has resulted in a superior dehumidification capacity, three critical challenges have restricted their performance.

Firstly, a higher regeneration temperature was required to achieve the desired dehumidification capacity [4]. Secondly, a high probability of deliquescence resulted in washing away of the desiccant coating from the metallic surface due to which operating

time was constrained to 2-3 min [5]. To overcome these challenges, we employed superabsorbent polymers (SAPs) comprising polyvinyl alcohol (PVA) as a replacement to silica gel [4]. We demonstrated that the composite polymer desiccant comprising PVA and LiCl improved the absorption capacity by 70-100% and absorbed moisture two times faster than silica gel. Additionally, a regeneration temperature ranging between 40-50°C was deemed to be sufficient.

The final challenge in using composite DCHEs for practical applications was due to the long-term corrosive effect of the hygroscopic LiCl/CaCl₂ salts. Potassium formate (HCO₂K) was used as an alternative salt due to its weakly organic and less corrosive nature. A 75w% HCO₂K combination with silica gel in DCHEs recorded only 20-30% improvement in the dehumidification capacity [6]. Although silica gel-HCO₂K composition improved DCHE's long term stability, key drawbacks on deliquescence and regeneration temperature remained unaddressed. Therefore, combining a suitable superabsorbent polymer with HCO₂K is indispensable to address the fundamental issues limiting the performance of DCHEs. To the best of our knowledge, no research has been carried out on the development of SAP-HCO₂K based desiccants and their application in desiccant dehumidifiers. Since combining PVA with HCO₂K in water results in a heterogeneous mixture [7], we propose developing composite desiccants comprising sodium polyacrylate based SAP with different concentrations of HCO₂K. Then through a series of static and dynamic characterization experiments, the most effective concentration of HCO₂K in SAP will be determined. Further, the composite polymer desiccant will be coated on a heat exchanger, and its quantitative improvement in dehumidification and thermal performance will be comprehensively evaluated.

2. EXPERIMENTAL METHODS AND PERFORMANCE PARAMETERS

2.1 Desiccant coating and material characterization

Sodium acrylate based SAP and appropriate amount of HCO₂K powders were mixed with deionized water at 60°C to produce SAP/HCO₂K solutions with five concentrations (0w%, 16.7w%, 33.3w%, 50w%, and 66.7w%) of HCO₂K. Clean and dry heat exchangers were dip-coated multiple times with the prepared desiccant solution and were dried in the oven at 80°C. The heat exchangers were weighed before and after coating to determine the amount of desiccant coated. A 1 cm² desiccant coated sheet was studied in the AQUADYNE

DVS gravimetric chamber. The desiccant's isothermal equilibrium capacity (q_e) was obtained at 30°C when the RH was regulated in steps from 0% to 95%. Finally, the surface morphology of the desiccant-coated sheet was obtained using a field emission scanning electron microscope (FESEM).

2.2 Dynamic performance testing facility

A testing facility was established for evaluating the dynamic performance of DCHEs, as shown in Fig. 1. Outdoor air was drawn into the system and was passed through the air heater and ultrasonic humidifier to achieve the required inlet conditions. The air was then made to interact with the DCHEs to allow the desiccant to absorb moisture. The cooling water flowing through the tubes captured the heat of sorption, and as a result, cool and dry air was obtained. At the end of the desired cycle time for dehumidification, the cycle was switched to the regeneration process. Hot water and indoor air flowing through the system were respectively replaced with cooling water and outdoor air flow. In the study, the cycle time (t_{cyc}) and hot water temperature ($T_{hw,in}$) were varied as specified in Table 1. The inlet air temperature, humidity ratio, air flow rate, and cooling water temperature were maintained relatively stable at 30°C, 21.5 g/kg, 55 kg/h, and 30°C, respectively.

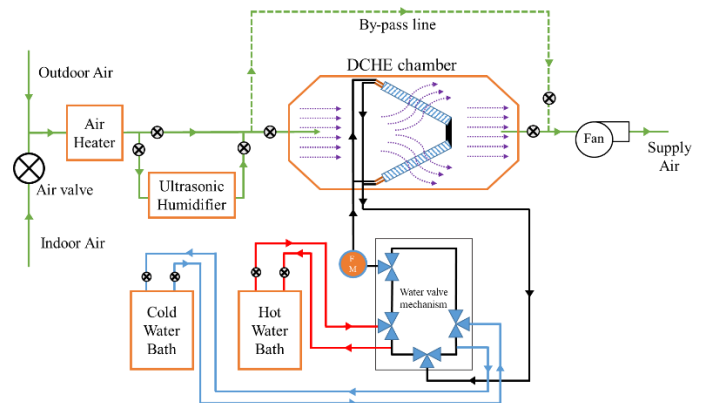


Fig. 1 A schematic of the testing facility of DCHE

Table 1 Operating conditions of the experiments

Parameters	Baseline	Variation
Cycle time (min)	10	5-30
Hot water temperature (°C)	50	40-70

2.3 Performance parameters

Moisture removal capacity (MRC) and thermal coefficient of performance (COP_{th}) are two key performance parameters that respectively define DCHE's dehumidification capacity and energy efficiency [8]. MRC

calculates the average amount of moisture removed per kg of dry air flowing over the DCHE for a specified cycle time as shown in eq. (1).

$$MRC = \frac{1}{t_{cyc}} \int_0^{t_{cyc}} (\omega_{a,in} - \omega_{a,out}) dt \quad (1)$$

COP_{th} evaluates how efficiently the energy supplied in DCHE is used for reducing the total cooling load of the air and is represented as,

$$COP_{th} = \frac{\dot{m}_a (h_{a,in} - h_{a,out})}{\dot{m}_w C_{p,w} (T_{hw,in} - T_{hw,out})} \quad (2)$$

3. RESULTS AND DISCUSSION

3.1 Isothermal equilibrium capacity

Pure ceramic desiccants such as silica gel and zeolite possess a maximum equilibrium capacity of 30-40% [2]. With the addition of hygroscopic salts, their sorption capacity increases by two times. Fig. 2 shows the sorption isotherms of the composite SAP with different concentrations of HCO₂K. The sorption capacity markedly improves with the systematic increase in the salt concentration. The hygroscopic salt attracts a higher quantity of water vapor and increases the interstitial volume of the polymer molecules. Consequently, the maximum sorption capacity of the composite polymer

3.2 DCHE and surface morphology

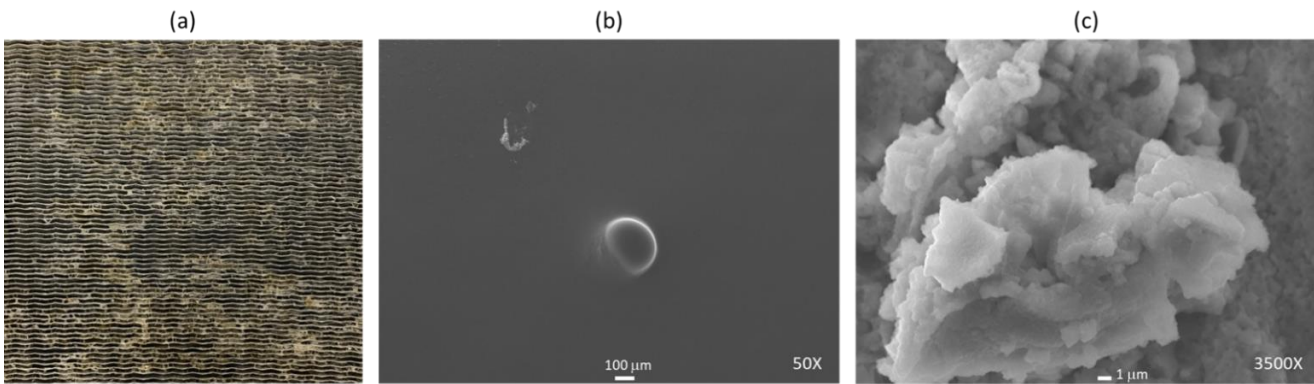


Fig. 3 (a) A photograph of the desiccant coated heat exchanger fin; (b)-(c) FESEM images of SAP-HCO₂K (50w%) coated Al fin at 50x and 3500x magnification scales

Fig. 3 (a) shows the SAP-HCO₂K (50w%) coating on a fin tube heat exchanger. The desiccant has continuous contact with the metallic surface without any requirement for an organic/emulsion binder. The corresponding SAP-HCO₂K (50w%) coating layer thickness and mass per unit area are 70 μm and 90 g/m², respectively. The desiccant-coated fin was then examined under a FESEM. Fig. 3 (b) shows that at 50x

desiccant is 4-8 times higher than pure and composite silica gel based desiccants.

When compared with PVA-LiCl desiccants, the sorption capacity of SAP-HCO₂K is only 10-15% lower [4]. Therefore, employing SAP-HCO₂K desiccants in DCHEs present great potential in enhancing the long term performance of DCHEs. 50w% HCO₂K in the polymer desiccant is considered appropriate for coating on heat exchangers as the difference in the equilibrium uptake is marginal between 50w% and 66.7w% HCO₂K.

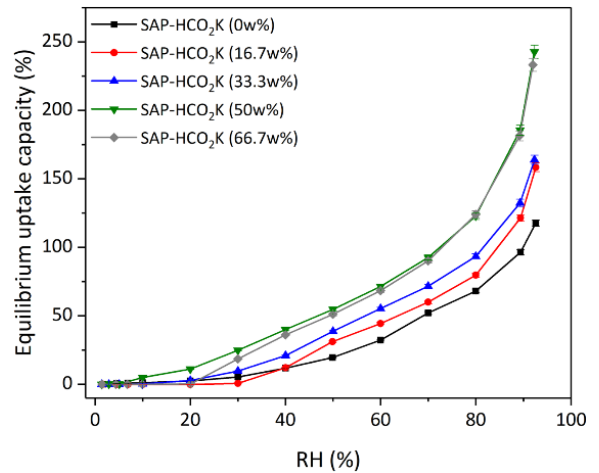


Fig. 2 Sorption isotherms of composite SAP desiccant comprising 0w% to 66.7w% concentration of HCO₂K at 30°C

magnification, the composite polymer coating is predominantly smooth with minor particle lumps. When further magnified around these particles, the cloudlike nature of the composite polymer desiccant can be observed, as illustrated in Fig. 3 (c). The average length of the particle is about 7-10 μm.

3.3 Dynamic performance evaluation

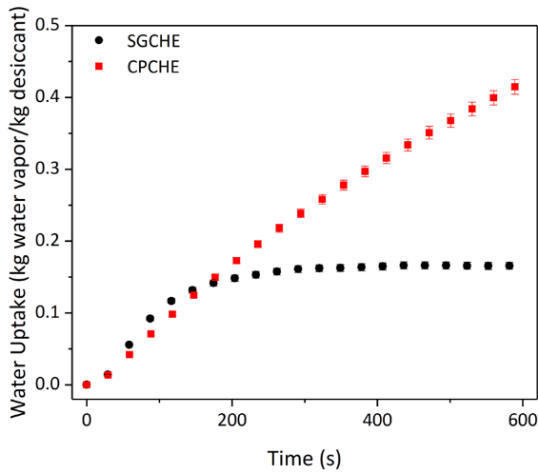


Fig. 4 Transient water uptake rate of silica gel and composite polymer DCHes normalized by the initial dry mass

Fig. 4 portrays the normalized transient water uptake of silica gel and composite polymer based DCHes under the baseline conditions. Silica gel coated heat exchanger (SGCHE) absorbs moisture rapidly until 120s because its moisture diffusivity is 2-3 orders higher than that of the composite polymer coated heat exchanger (CPCHE). However, after 260s, the moisture uptake of SGCHE is marginal whereas CPCHE shows a linear increase until the end of the cycle time. The increase in moisture uptake of CPCHE is attributed to the composite polymer's higher sorption potential while silica gel saturates faster due to its moderate sorption capacity.

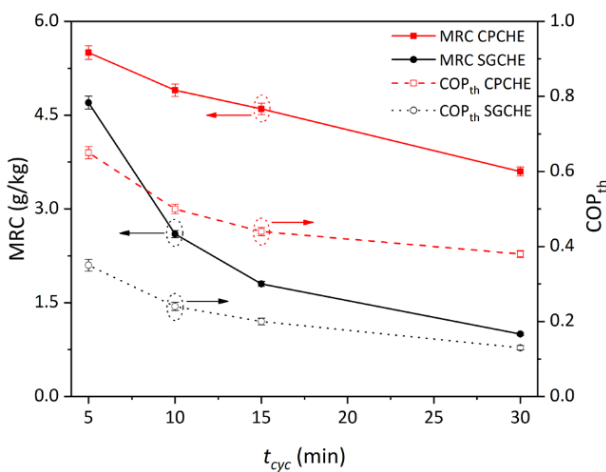


Fig. 5 Effect of cycle time on MRC and COP_{th}

Fig. 5 indicates that MRC and COP_{th} of the CPCHE respectively drop by 26% and 32% when cycle time (t_{cyc}) is controlled between 5-30 min. Nevertheless, for SGCHE, MRC reduces by two times and COP_{th} drops by 30% when t_{cyc} is regulated between 5-10 min. While greater t_{cyc} is favorable, the sorption potential and thermal efficiency of the DCH is significantly reduced.

As a result, $t_{cyc} = 5$ min or less is suitable for SGCHE and t_{cyc} controlled between 10-15 min is advantageous for CPCHE. It is worthy to note that CPCHE records at least two times improvement in both MRC and COP_{th} as compared to SGCHE.

The effect of variation of hot water or regeneration temperature ($T_{hw,in}$) on the performance of SGCHE and CPCHE is shown in Fig. 6. Rise in $T_{hw,in}$ enhances moisture desorption rate, thereby increasing the water sorption ability for the subsequent cycles. Consequently, respective improvements of 50% and 39% are observed in the MRC and latent load removal of SGCHE and CPCHE. When $T_{hw,in}$ is controlled between 40-60°C, air temperature is also reduced, and the sensible load is removed from the air. Conversely, surplus heat is added to the air during the dehumidification process when $T_{hw,in}$ is raised beyond 60°C. It is worthy to note that the magnitude of the sensible load added/removed depends on the thermal mass of the heat exchanger and the sorption heat of the desiccant. Since identical heat exchangers have been employed, the thermal mass is predominantly similar. Moreover, the sorption heat of both the desiccants is comparable as the difference between the sensible load removed for SGCHE and CPCHE is marginal. While $T_{hw,in}$ presents contrasting effects on sensible and latent load removal, the total cooling load removed from the air is almost independent of $T_{hw,in}$. Contrary to the improvement in dehumidification capacity, the thermal process efficiency of the DCH system drops by 100-150% when $T_{hw,in}$ is raised between 40-70°C. Therefore, the regeneration temperature ranging between 40-50°C, similar to the PVA-LiCl coated heat exchangers, can be adopted for operating CPCHEs at their highest COP_{th} .

4. CONCLUSIONS

In this study, we have developed a composite desiccant with equal concentrations of sodium polyacrylate based superabsorbent polymer (SAP) and potassium formate (HCO_2K) salt. Key characterization experiments demonstrated that the composite SAP- HCO_2K desiccant records 4-8 times improvement in sorption capacity when compared to pure/composite silica gel. Further, no additional binder is required to achieve continuous contact of the composite polymer desiccant on the metallic surface.

While the hot water temperature has marginal effect on the total cooling load removed, selecting the lowest suitable regeneration temperature is necessary to achieve greater energy efficiency of the DCH system. The composite polymer coated heat exchanger paves the

way for sustainable air dehumidification as it undergoes markedly less number of regeneration cycles and records two times improvement in the dehumidification capacity and thermal coefficient of performance.

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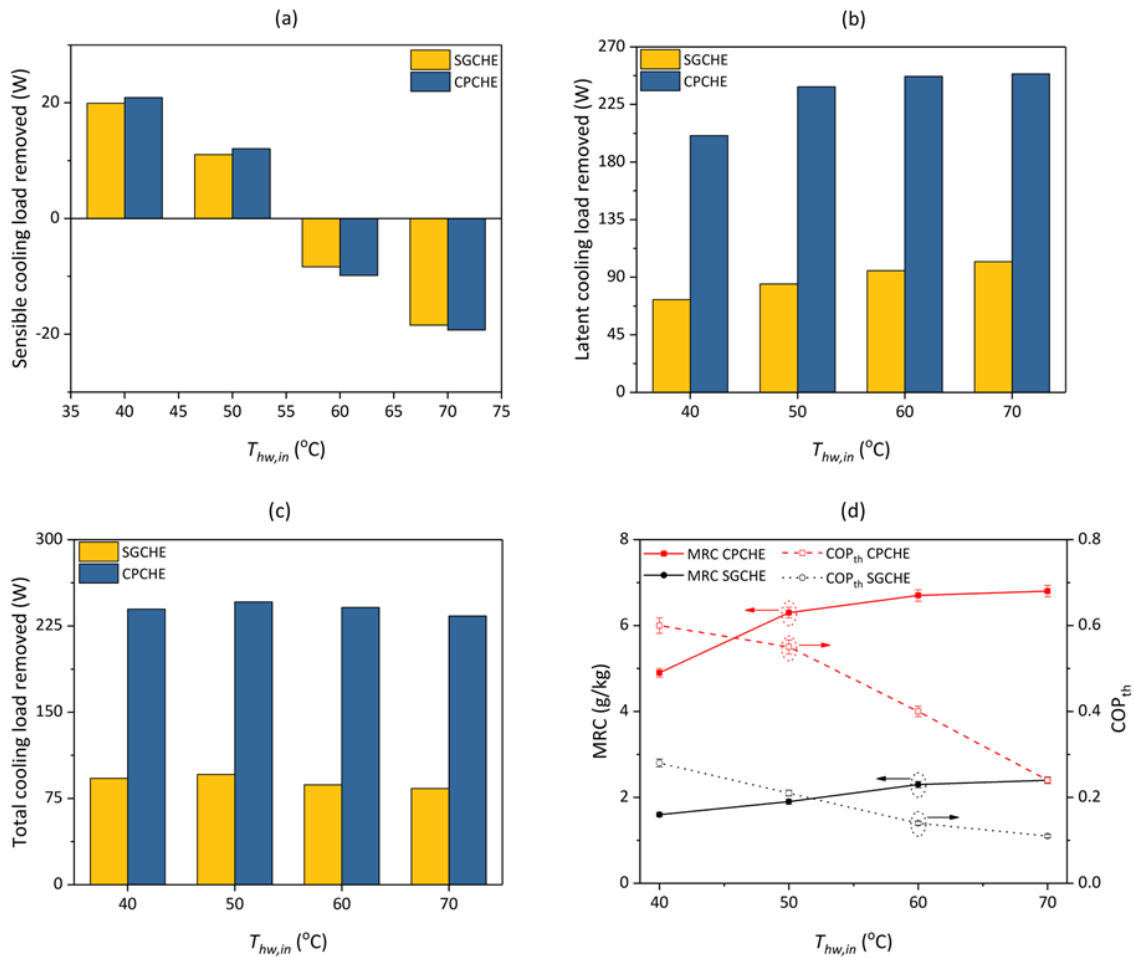


Fig. 6 Effect of hot water temperature on (a) sensible load; (b) latent load; (c) total cooling load; and (d) MRC and COP_{th}

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