Experimental study of a membrane-based dehumidification cooling system

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Abstract

Membrane-based liquid desiccant dehumidification has attracted increasing interests with elimination of solution droplets carryover problem. In this study, a membrane-based hybrid liquid desiccant dehumidification cooling system is developed, which is mainly composed of a dehumidifier, a regenerator and an evaporative cooler. The system is capable to remove latent load by the liquid desiccant dehumidification unit and simultaneously to handle sensible load with an evaporative cooling unit. This paper presents a performance evaluation study of the hybrid system with calcium chloride as liquid desiccant based on experimental data. Series of tests are conducted to identify influences of operating variables and conditions (i.e. desiccant solution concentration ratio, regeneration temperature, inlet air condition, etc.) on the system performance. The experimental results indicate that the system is viable for dehumidification cooling purpose. Furthermore, it is noteworthy that mass balance between the dehumidifier and regenerator should be achieved for system steady operation. Thermal COP_{th} of 0.70 and

electrical COP_{el} of 2.62 are achieved respectively under steady operating condition at $CaCl_2$ concentration ratio of 36%.

Keywords: Liquid desiccant, Dehumidification, Regeneration, Membrane, Experimental tests

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Nomenclature

c_p	Specific heat capacity (J/kg.K)
h	Specific enthalpy (J/kg.K)
m	Mass (kg)
$\dot{m}$	Mass flow rate (kg/s)
$\dot{M}$	Moisture change rate (g/s)
P	Pressure (Pa)
$\dot{Q}$	Input/ Output Power (W)
T	Temperature (°C)
x_i	Measured variable
U_x	Measured variable uncertainty
U_y	Variable uncertainty
v	Volumetric flow rate (L/min)
V	Volume (m^3)
W_e	Total electrical requirement (W)

Greek symbols

η	Effectiveness
ρ	Density (kg/m^3)
ω	Air humidity ratio (kg/kg_{dryair})

Subscripts

a	Moisture addition
air	Air
c	Cooling
eq	Equilibrium state
fl	Flow meter float
in	Inlet
out	Outlet
r	Moisture removal
sol	Solution
w	Water

Abbreviations

COP	Coefficient of performance
DH	Dehumidifier
RE	Regenerator

1. Introduction

Desiccant cooling has been regarded as an environmental-friendly air conditioning technology without shortcomings of overcooling and reheating [1]. Compared to the solid desiccant system, the liquid desiccant system is more economical and flexible in utilization of low-grade energy sources [2] and efficient in providing high quality supply air with independent humidity and temperature controls [3]. Generally, the selection of a liquid desiccant depends on various parameters, like boiling point elevation, energy storage density, regeneration temperature, thermophysical property, availability and cost [4]. Particularly, halide salts are mostly preferred, for example lithium chloride (LiCl), lithium bromide (LiBr) and calcium chloride ($CaCl_2$). Comparatively, $CaCl_2$ is the cheapest and most readily available desiccant [5]. On the other hand, a variety of packing types of the liquid desiccant system have been developed, such as wetted wall, spray tower, packed column and membrane-based [6]. Among them, the membrane-based configuration providing an indirect contact for dehumidification has attracted more interests owing to the elimination of solution carryover problem. In operation, membranes allow heat and moisture transfer between solution and process airstream, whereas meanwhile prevent the entrainment of liquid desiccant [7].

Many studies of the membrane-based liquid desiccant cooling system have been conducted, which incorporates different renewable energy sources and cooling technologies. For instance, Abdel-Salam, et al. [8] proved the feasibility of a membrane-based desiccant air conditioning system powered by solar energy. El-Dessouky, et al. [9] proposed a new air conditioning system consisting of a membrane dehumidification unit and a direct evaporative cooler, and they observed that 86.2% energy saving can be achieved compared to a conventional stand-alone vapour compression system. In addition, Jradi and Riffat [10] developed a hybrid dehumidification cooling system integrated with an indirect evaporative cooler, with which the supply air temperature and humidity reduce from 33.8℃ to 22.3℃ and 68.6% to 35.5% respectively. However, yet limited researches have been carried out for feasibility study and performance evaluation of the membrane-based liquid desiccant dehumidification cooling system through experimental work. In this study, a membrane-based hybrid dehumidification cooling system with heat recovery is built for experimental investigations. Feasibility of the system for hot and humid regions is assessed and influences of various operating variables, including inlet air condition, desiccant concentration ratio and regeneration temperature on the dehumidifier, regenerator and overall system performances are evaluated based on the experimental results.

2. Experimental set-up

The proposed hybrid system is mainly composed of a dehumidifier, a regenerator, an evaporative cooler and an air-to-air heat exchanger, as shown in Fig. 1. Three processes are involved during operation, namely: dehumidification, regeneration and evaporative cooling. Additionally, the airstream from the evaporative cooler is used to cool the dry air to meet the supply requirement in the air-to-air heat exchanger. After dehumidification, the dilute solution flows into the weak solution storage tank and is delivered by magnetic-driven pump to a heat exchanger (HX2), where the weak solution is pre-heated before being heated by heat source. To enhance the dehumidification performance, cold water cools the strong desiccant solution prior to flowing into the dehumidifier and then flows directly into the evaporative cooler.

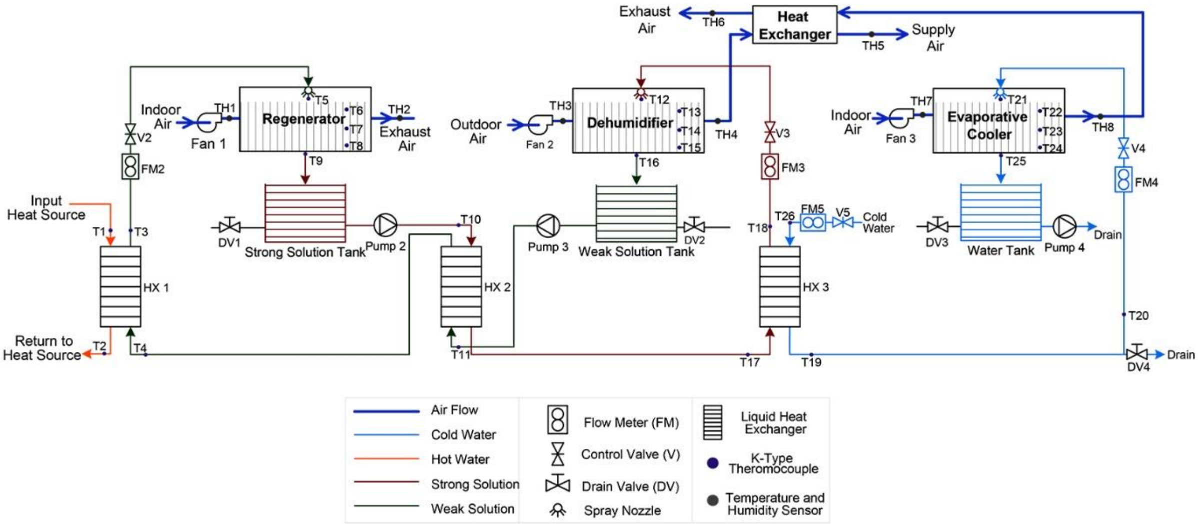


Fig. 1. Schematic graph of the membrane-based dehumidification cooling system

Membrane-based units for the dehumidifier and regenerator are designed with a dimension of 410mm (Length) × 230mm (Width) × 210mm (Height), as depicted in Fig. 2. For the evaporative cooler with the same dimension, air channels are formed by fibre without membrane sheets, which provides wet surface as cold water flowing downwards.

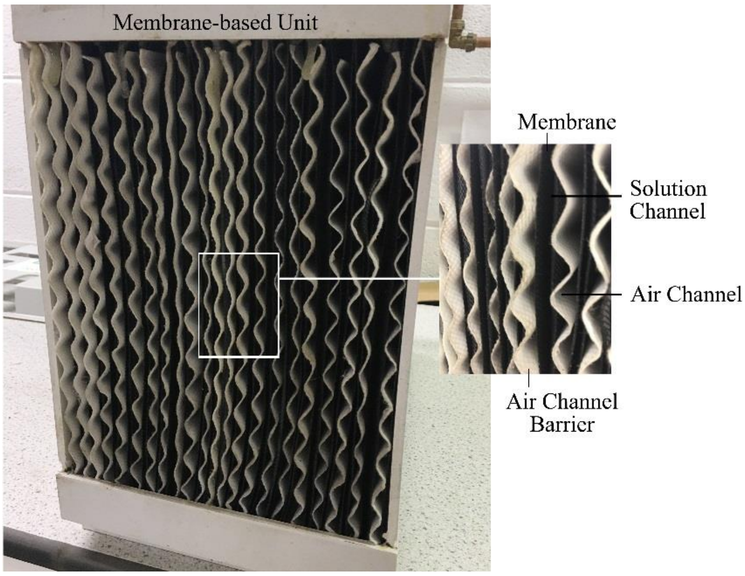


Fig. 2. Photo of the membrane-based unit

2.1 Experiment method

A boiler is utilized as the heat source for regeneration in the experiment and $CaCl_2$ solution is selected as the liquid desiccant. A photo of the system test rig is presented in Fig. 3. Insulations are applied for air ducting, pipe work and heat exchangers to reduce the surrounding effects. Main experimental equipment with their specifications is provided in Table 1.

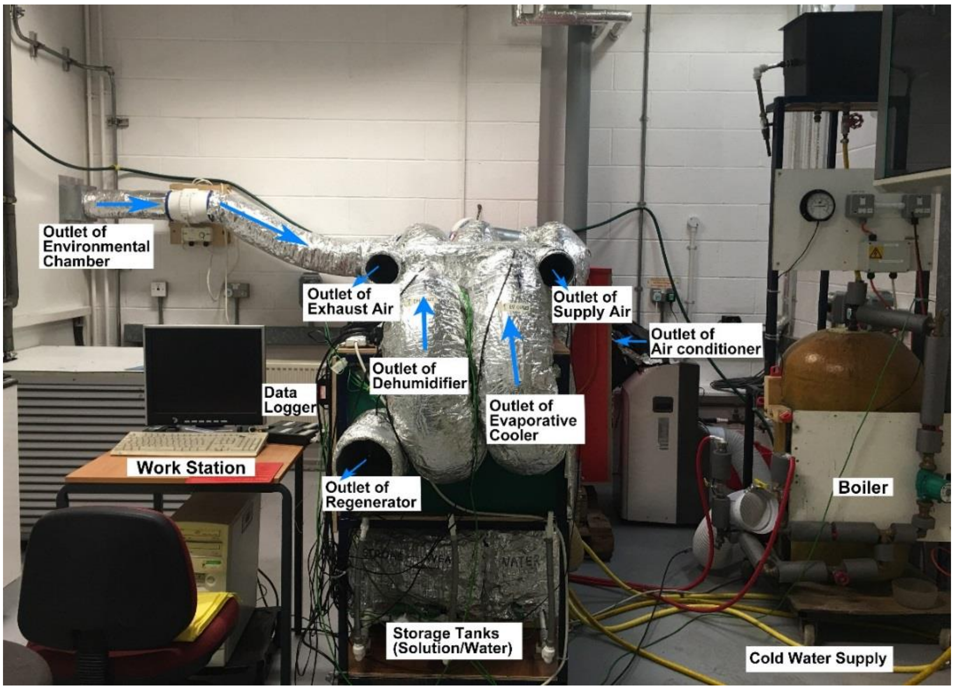


Fig. 3. Test rig photo

Table 1. Specifications of main equipment

Equipment	Properties		Manufacturer
Magnetic pump	Power	15 W	Shanghai Jiaxing Pumps Co., Ltd.
	Maximum frequency	50 Hz	
	Maximum speed	2600 r/min	
	Maximum capacity	10 L/min	
AC axial fan	Power	45W	ebm-papst Mulfingen GmbH & Co. KG
	Nominal speed	2800 min^{-1}	
Boiler	Capacity	3kW	Wilo SE
	Supply temperature range	50-80°C	
	Water storage	120 Litre	

	Circulating pump	45W	
	Water flow rate	0-6 L/min	

Main measurement instruments with their respective accuracies are listed in Table 2. Series of K-type thermocouples are employed to measure temperatures of desiccant solution and water flows. Humidity and temperature probes are installed at all air inlets and outlets, and associated air velocities are measured with an anemometer. A hydrometer is used to obtain the solution density. Thus, $CaCl_2$ solution concentration ratio can be determined with correlation on a basis of solution density and temperature [11]. Moreover, volumetric flow rates of liquid flows (i.e. desiccant solution and water) are measured by float-style flow meters, which are calibrated with water at 20°C. In order to equate an actual desiccant solution flow rate in dehumidifier and regenerator units with a reading from the flow meter, the correction correlation given in literature [12] is needed:

$$v_{\mathrm{sol}} = v_{\mathrm{w}} \sqrt{(m_{\mathrm{fl}} - V_{\mathrm{fl}}\rho_{\mathrm{sol}})\rho_{\mathrm{w}} / (m_{\mathrm{fl}} - V_{\mathrm{fl}}\rho_{\mathrm{w}})\rho_{\mathrm{sol}}} \qquad (1)$$

where, v_{sol} and v_{w} are volumetric flow rates of the desiccant solution and water respectively, L/min. ρ_{sol} and ρ_{w} are densities of solution and water, kg/m^3. For the flow meter, the float weight (m_{fl}) is 2.1×10^{-3} kg and volume (V_{fl}) is $0.25\times10^{-6}\mathrm{m}^3$.

Table 2. Specifications of measurement instruments

Devices	Measurement Range	Accuracy
RS K-type thermocouple probe	0-1100°C	±0.75%
Sensirion EK-H4 humidity sensor	-40 - +125°C	±0.3%
	0 - 100% RH	±2%
Parker liquid flow indicator	4-22 L/min	±2%
Testo thermo-anemometer 405	0-10 m/s	±5%
Brannan hydrometer 200 Series	1.0-1.6 g/m^3	±2%
Data logger DT500	Data Acquisition	±0.15%

The experimental data are processed with uncertainty analysis, which provides the associated error of a calculated value. Error bars are included in the graphs for experimental result analyses.

$$U_y = \sqrt{\sum_{i=1}^{N} \left(\frac{\partial y}{\partial x_i}\right)^2 \cdot {U_{x_i}}^2} \quad (2)$$

where, U_{xi} is uncertainty of each measured variable x_i.

2.2 Evaluation Method

Dehumidification process

The dehumidification performance is assessed by moisture removal rate.

$$\dot{M}_{\mathrm{r}} = \dot{m}_{\mathrm{air\_DH}} \cdot (\omega_{\mathrm{in\_DH}} - \omega_{\mathrm{out\_DH}}) \quad (3)$$

where, $\dot{M}_{\mathrm{r}}$ represents moisture removal rate, g/s. $\dot{m}_{\mathrm{air\_DH}}$ is mass flow rate of air passing through the dehumidifier, kg/s, $\omega_{\mathrm{in\_DH}}$ and $\omega_{\mathrm{out\_DH}}$ are air humidity ratios at inlet and outlet of the dehumidifier, kg/kg$_{\mathrm{dryair}}$. Thermophysical properties of the moist air are determined using equations referred to literature [13].

The dehumidification effectiveness is defined as the ratio of actual change in moisture content to the maximum moisture transfer.

$$\eta_{\mathrm{DH}} = \frac{\omega_{\mathrm{in\_DH}} - \omega_{\mathrm{out\_DH}}}{\omega_{\mathrm{in\_DH}} - \omega_{\mathrm{eq\_DH}}} \quad (4)$$

where, η_{DH} is the dehumidification effectiveness. $\omega_{\mathrm{eq\_DH}}$ is equilibrium humidity ratio of desiccant solution at the inlet condition, kg/kg$_{\mathrm{dryair.}}$ Under the equilibrium state, it is given by literature [14]:

$$\omega_{\mathrm{eq\_DH}} = 0.62198 \times \frac{P_{\mathrm{sol}}}{P_{\mathrm{A}} - P_{\mathrm{sol}}} \quad (5)$$

where, P_A is atmospheric pressure, Pa, and P_{sol} is vapour pressure of $CaCl_2$ solution at a given temperature, Pa, which can be calculated with the empirical correlation derived by literature [15].

Based on the enthalpy difference between the inlet and outlet air in the dehumidifier, the dehumidifier cooling output is determined as:

$$\dot{Q}_{\mathrm{DH\_c}} = \dot{m}_{\mathrm{air\_DH}}(h_{\mathrm{in\_DH}} - h_{\mathrm{out\_DH}}) \tag{6}$$

where, $\dot{Q}_{\mathrm{DH\_c}}$ is the dehumidifier cooling output, W. $h_{\mathrm{in\_DH}}$ and $h_{\mathrm{out\_DH}}$ are specific enthalpies of air at inlet and outlet of the dehumidifier, J/kg.

Regeneration process

The regeneration performance is evaluated by moisture addition rate.

$$\dot{M}_{\mathrm{a}} = \dot{m}_{\mathrm{air\_RE}} \cdot (\omega_{\mathrm{out\_RE}} - \omega_{\mathrm{in\_RE}}) \tag{7}$$

where, $\dot{M}_{\mathrm{a}}$ represents moisture addition rate, g/s. $\dot{m}_{\mathrm{air\_RE}}$ is regenerator air mass flow rate, kg/s. $\omega_{\mathrm{in\_RE}}$ and $\omega_{\mathrm{out\_RE}}$ are humidity ratios of air entering and leaving the regenerator, kg/kg_{dryair}.

The thermal input power of the regenerator is determined as:

$$\dot{Q}_{\mathrm{RE}} = \dot{m}_{\mathrm{w\_RE}} \cdot c_{\mathrm{p\_w\_RE}}(T_{\mathrm{w\_in}} - T_{\mathrm{w\_out}}) \tag{8}$$

where, $\dot{Q}_{\mathrm{RE}}$ is the regenerator thermal input power, W. $\dot{m}_{\mathrm{w\_RE}}$ and $c_{\mathrm{p\_w\_RE}}$ are water mass flow rate, kg/s, and specific heat capacity, J/kg, in the heating circuit. $T_{\mathrm{w\_in}}$ and $T_{\mathrm{w\_out}}$ are hot water supply and return temperatures respectively, °C.

Coefficient of performance

The total cooling output power of the hybrid system is expressed as:

$$\dot{Q}_{\mathrm{c}} = \dot{m}_{\mathrm{air\_DH}}(h_{\mathrm{in\_DH}} - h_{\mathrm{supply}}) \tag{9}$$

where, $\dot{Q}_{\mathrm{c}}$ is the system total cooling output power, W. h_{supply} is specific enthalpy of supply air, J/kg.

The hybrid system overall coefficients of performance (COP) are defined as:

$$\mathrm{COP}_{\mathrm{th}} = \frac{\dot{Q}_{\mathrm{c}}}{\dot{Q}_{\mathrm{RE}}} \tag{10}$$

$$\mathrm{COP}_{\mathrm{el}} = \frac{\dot{Q}_{\mathrm{c}}}{W_{\mathrm{e}}} \tag{11}$$

where, $\mathrm{COP}_{\mathrm{th}}$ is thermal coefficient of performance and $\mathrm{COP}_{\mathrm{el}}$ is electrical coefficient of performance. W_{e} is electrical consumption, W.

3. Results and Discussion

Table 3 presents operating variables for the experiment. Effects of operating variables on the dehumidifier and regenerator performances are investigated at $CaCl_2$ solution concentration ratio of 39%.

Table 3. Operating variables for experiment

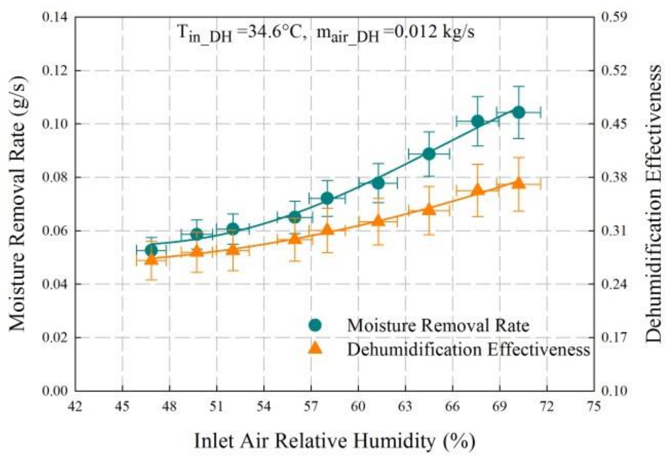
Variables	Range	
Dehumidifier		
Desiccant solution flow rate	1 L/min	
Solution concentration ratio	30-42%	
Air volumetric flow rate	35 m^3/hr	
Inlet air condition	34-35°C	50-75% RH
Regenerator		
Hot water supply temperature	55-80°C	
Hot water supply flow rate	2 L/min	
Desiccant solution flow rate	1 L/min	
Air volumetric flow rate	44-148 m^3/hr	
Inlet air condition	26°C	33% RH

Evaporative cooler		
Inlet air condition	26°C	33% RH
Cold water supply temperature	10°C	
Cold water supply flow rate	12 L/min	

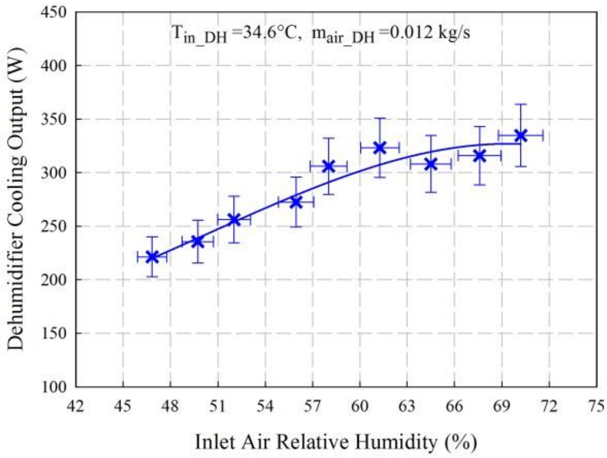
3.1 Effect of inlet air relative humidity on dehumidification performance

The inlet air temperature for the dehumidifier is set at 34.6°C and relative humidity varies from 46% to 70%. It can be seen from Fig. 4(a) that the dehumidifier performance increases with the inlet air relative humidity at the constant inlet air temperature. The dehumidifier moisture removal rate doubles as air relative humidity increases from 46% to 70% and the dehumidification effectiveness improves by 36.9%. The increase in the moisture removal rate is caused by the greater vapour pressure difference between the airstream and desiccant solution.

Over the investigated inlet air relative humidity range, the higher inlet air relative humidity leads to more cooling output as shown in Fig. 4(b). The dehumidifier cooling output increases from 221.4W to 334.7W as air relative humidity increases from 46% to 70%. However, as the relative humidity gets higher than 63%, the increase in the cooling output becomes smaller. It indicates that the dehumidifier cooling output approaches the maximum capacity with further increase in air relative humidity.



(a)



(b)

Fig. 4. Effects of inlet air relative humidity on (a) moisture removal rate and dehumidification effectiveness and (b) dehumidifier cooling output

3.2 Effect of air flow rate on regeneration performance

Tests are carried out to investigate air flow rate effect on the regeneration performance. At an inlet air temperature of 26°C and relative humidity of 33%, the regenerator air flow rate is increased from 43.82m^3/hr to 148.44m^3/hr, while the hot water is kept at a temperature of 61°C. Though the increase of regenerator air flow rate leads to reduction in the moisture addition capability, the moisture addition rate takes both the moisture content change and air flow rate into account. As observed in Fig. 5, there is an increase in the moisture addition rate. However, the moisture addition rate only increases by 0.04g/s over the investigated air flow rate range, which indicates that the impact of the air flow rate on regeneration performance is not very significant.

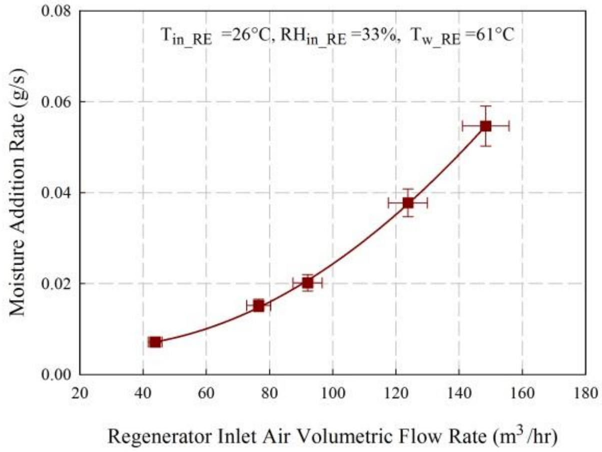


Fig. 5. Effects of air flow rate on moisture addition rate

3.3 Effect of hot water temperature on regeneration performance

To identify the effect of hot water temperature on regeneration performance, the hot water is supplied in the temperature range from 55°C to 80°C. As presented in Fig. 6, the regeneration performance improves accordingly with hot water temperature under the constant regenerator inlet condition. The moisture addition rate increases by 75% as the hot water temperature increases from 55°C to 80°C. The increase in hot water temperature results in higher desiccant solution temperature in the regenerator, and thus higher vapour pressure is obtained in solution side. Then the greater vapour pressure difference between the desiccant solution and airstream leads to more mass transfer in the regeneration process at the constant inlet air condition. Moreover, as the hot water temperature is above 70°C, it is noted that the increase in the moisture addition rate becomes smaller. The variation in the air humidity ratio across the regenerator is only 0.06g/kg_{dryair} as the hot water temperature rises from 70°C to 80°C. Therefore, regarding to the feasibility of utilizing renewable energy as heat source, at the given operating condition, hot water supply temperature up to 70°C is sufficient for adequate regeneration performance.

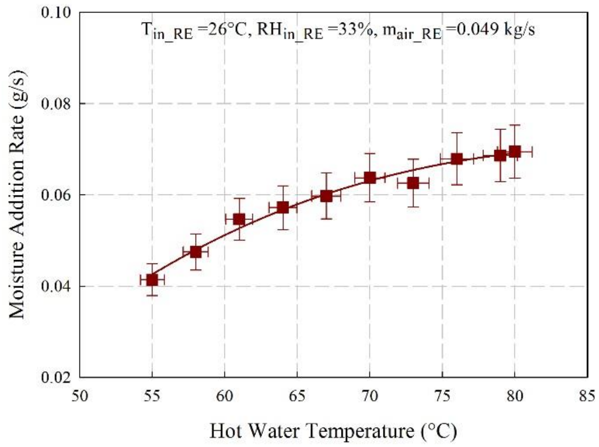


Fig. 6. Effect of hot water temperature on moisture addition rate

3.4 Effect of concentration ratio on system performance

According to the operative concentration ratio level of $CaCl_2$, investigations are conducted with solution concentration ratio ranging from 30% to 42%. The dehumidification effectiveness increases evidently with concentration ratio as shown in Fig. 7. For desiccant solution concentration ratio below 33%, there is only slight difference in the dehumidifier effectiveness, which implies the operative concentration ratio needs to be at least above 33%. As solution concentration ratio gets higher than 33%, the dehumidifier effectiveness improves more significantly and reaches up to 0.54 at concentration ratio of 42%. For operation of the liquid desiccant system, higher desiccant solution concentration ratio would be better for dehumidification performance. However, the use of highly concentrated solution may cause salt crystallization, which may lead to risks of fluid mal-distribution, channel blockage, high pumping pressure, and membrane fouling. On the other hand, the dehumidifier cooling output also increases from 181.0W to 428.8W with the increase of solution concentration ratio, which is related to the higher moisture removal rate in the dehumidifier.

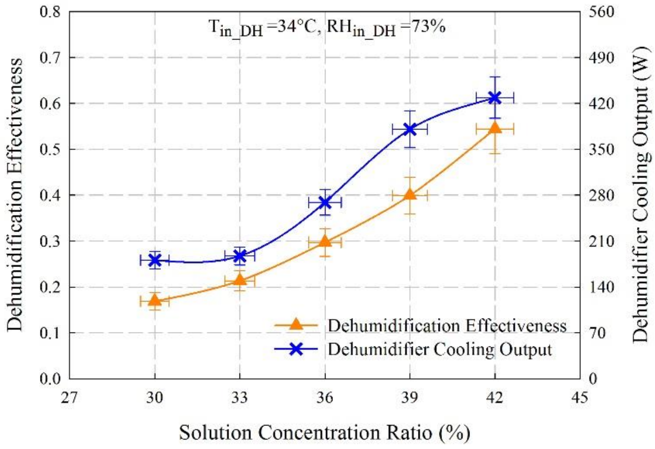


Fig. 7. Effects of solution concentration ratio on dehumidification effectiveness and cooling output

It can be observed from Fig. 8 that as concentration ratio increases from 30% to 42%, the dehumidifier moisture removal rate improves from 0.05g/s to 0.14g/s while the regenerator moisture addition rate decreases from 0.11g/s to 0.05g/s. For the dehumidification process, the driving force caused by the vapour pressure difference between airstream and desiccant solution gets higher for stronger solution, which thus leads to greater moisture removal rate in the dehumidifier. On the contrary, in the regeneration process, desiccant solution with higher concentration ratio has lower capability for moisture addition due to the lower vapour pressure.

To allow continuous operation of the overall system, the performance of regenerator should match with that of dehumidifier otherwise mass imbalance occurs, which would result in some problems such as the dilution of desiccant solution over time. For the investigated operating condition, the dehumidification and regeneration processes are balanced at desiccant solution concentration ratio of 36%, as the dehumidifier moisture removal rate equals to the regenerator moisture addition rate. Thus, measures are needed to facilitate the regenerator performance for the stronger desiccant solution while the dehumidification performance should be improved at lower concentration ratio. Under the system steady operation condition, the thermal COP_{th} and electrical

COP_{el} reach up to 0.70 and 2.62 respectively at concentration ratio of 36%, while the supply air temperature is provided at 20.4°C. Hence, the results reveal that the hybrid system is feasible for applications, and the supply air condition could meet the comfortable indoor environment requirement.

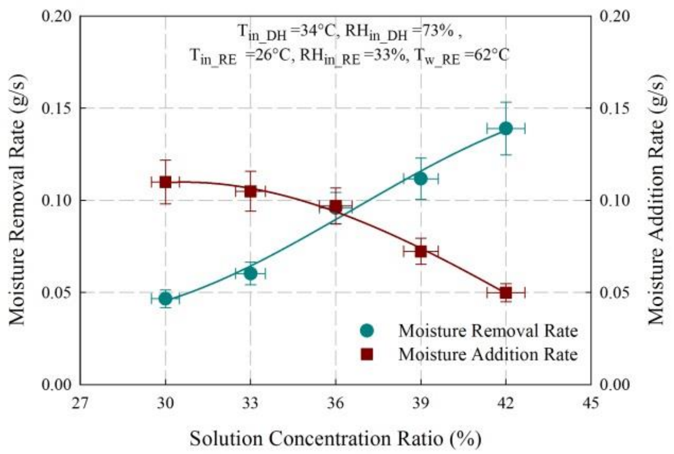


Fig. 8. Effects of solution concentration ratio on moisture removal and addition rates

4. Conclusions

A membrane-based hybrid liquid desiccant dehumidification cooling system is developed to provide efficient temperature and humidity controls in hot and humid regions. The experimental results indicate the system with $CaCl_2$ desiccant solution is feasible for dehumidification and cooling purposes under the tested hot and humid conditions. Impacts of operating variables on dehumidifier, regenerator and system performances are identified through experimental tests. As inlet air relative humidity increases from 46% to 70% at constant temperature of 34.6°C, the dehumidifier moisture removal rate doubles and dehumidification effectiveness improves by 36.9%. On the other hand, the regenerator performance increases with inlet air flow rate and hot water temperature. As the hot water temperature increases from 55°C to 80°C, the regenerator moisture addition rate increases by 75% under the same inlet air condition. By increasing the desiccant solution concentration ratio from 30% to 42%, the dehumidification performance improves from 0.05g/s to 0.14g/s and the dehumidifier cooling output doubles, while the regenerator moisture addition rate decreases by 54.5%. For steady system operation, mass balance between dehumidification and regeneration is of vital importance. Under the investigated solution concentration ratio of 36%, the supply air temperature of 20.4°C is obtained, the system thermal COP_{th} achieves up to 0.70 and electrical COP_{el} reaches to 2.62 accordingly.

Acknowledgements

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