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Energy Performance of Solar Assisted Desiccant Enhanced Evaporative Cooling Air conditioning System

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Abstract

The desiccant enhanced evaporative cooling system is proposed as a promising energy-saving air-conditioning (A/C) scheme. It consists of hybrid liquid desiccant dehumidifier and indirect evaporative cooler. The hot and humid air is firstly dehumidified by liquid desiccant dehumidifier (LDD) and then sensibly cooled by regenerative indirect evaporative cooler (RIEC). The LDD-RIEC system operates without electricity-intensive compressor but with low-power-consumption solution pumps and water pumps. The heat captured by the solar collector is used for regenerating the desiccant solution. The solar collector model, LDD model and RIEC model were established separately to facilitate the hybrid system simulation in a closed-loop. The influence of solar collector area is analyzed. The energy saving potential of the proposed system is quantitatively evaluated with respect to the mechanical vapor compressor refrigeration (MVCR) system. The results show that both the moisture remove rate and cooling capacity improves with the increase of solar collector area. The LDD-RIEC A/C system saves 47% energy consumption compared with MVCR system in Hong Kong summer days.

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Keywords: Liquid desiccant dehumidifier; Evaporative cooling; Hybrid cooling system; Solar collector; Energy saving

1. Main text Introduction

In subtropical areas, such as Hong Kong, the cooling season is long. It was reported the energy consumption of the air-conditioning (A/C) system accounted for about 54% and 23% of the total building energy consumption in Hong Kong's typical office and residential buildings. Traditional mechanical vapor compressor refrigeration

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(MVCR) system suffers from high energy consumption, poor humidity control and huge environmentally harmful CFCs.

To reduce the energy consumption of A/C system, the desiccant enhanced evaporative cooling system is proposed as a promising energy-saving scheme. The system consists of hybrid liquid desiccant dehumidifier (LDD) and regenerative indirect evaporative cooler (RIEC). The LDD stands out as an effective technology to deal with the latent heat. Unlike MVCR system, the LDD is unnecessary to reduce the air temperature below the dew-point temperature and avoids reheat energy waste. It uses the partial pressure difference of water vapor between the reversed moist air flow and falling liquid desiccant for moisture removal. Besides, the LDD could be driven by low grade heat sources, such as solar energy and waste heat, for further improving energy efficiency. The RIEC is well-recognized for effectively cooling the air by water evaporation. The RIEC is consisted of a series of thin parallel plates assembled to form multi-layer alternating dry and wet channels. The water drop sprayed into the wet channels and cools the plate surface with aid of water film evaporation. The fresh air in the dry channel is sensibly cooled by the low temperature plate. As an advanced indirect evaporative cooler (IEC), the cooling efficiency of RIEC is higher than that of traditional IEC. Both the LDD and RIEC are low-energy-consumed equipment in which there are only water pump and solution pumps for operation.

The performances of hybrid desiccant dehumidification and evaporative cooling system have been numerically and experimentally studied [3]. Various system configurations were proposed by adopting either solid desiccant or liquid desiccant and different types of IEC. The regeneration heat source including electrical heater, solar collector and industry waste heat were used in different studies. It is found that previous researches focus on system modeling, parameter analysis and energy saving prediction. However, most existing studies related to hybrid system modeling are based on the multi-parameter fitting formula of components. Although accurate differential equation models have also been used in some studies, they were mainly open-loop based system simulation, which not considers the close-loop relationship of solution temperature and concentration between the dehumidifier and regenerator. Besides, the influence of solar collector area has not been investigated in detail.

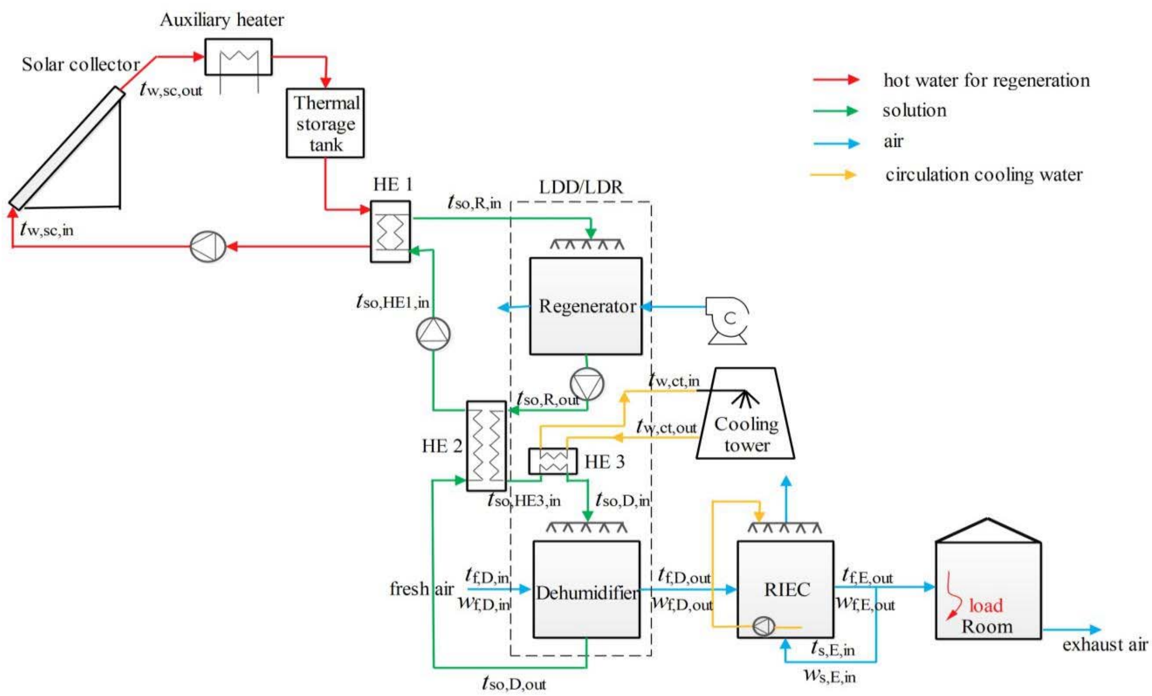

Fig. 1 Diagram of LDD-RIEC system

In the paper, the LDD-RIEC A/C system was explored to deal with 100% fresh air. The diagram of the proposed system is shown in Figure 1. The fresh air is centralized processed by the solar-assisted LDD-RIEC system and supplied to indoor by air ducts. The heat captured by the solar collector is used for desiccant solution regeneration through a water/solution heat exchanger (HE1). Auxiliary heater would operate in case of thermal energy is insufficient for regeneration. Storage tank is used for storing excess heat. As the dehumidification efficiency decreases with the increases of inlet solution temperature, a cooling tower is used for cooling desiccant solution through a solution/water heat exchanger (HE3). The lithium chloride (LiCl) solution is used as desiccant.

Nomenclatures			
A	heat transfer area/solar collector area, m^2	h_{fg}	latent heat of vaporization of water, J/kg
I	solar radiation, W/m^2	i	enthalpy of air, J/kg
Q	heat transfer rate, W	m	mass flow rate, kg/s
c_{pa}	specific heat of air, J/kg·℃	r	extract air ratio of RIEC
c_{pw}	specific heat of water, J/kg·℃	s	channel gap, m
c_{pso}	specific heat of solution, J/kg·℃	t	celsius temperature, ℃
d_e	hydraulic diameter, m	u	air velocity, m/s
h	heat transfer coefficient, W/m^2·℃	xs	mass fraction of desiccant solution
h_m	mass transfer coefficient, kg/m^2·s		
Greek symbols			
ω	moisture content of air, kg/kg	η	efficiency
Subscripts			
f	fresh/ primary air	wb	wet-bulb
r	return air	lat	latent heat
s	secondary air	sen	sensible heat
w	wall/water	sat	saturated
ew	evaporation water	sup	supply air
in	inlet	ct	cooling tower
out	outlet	D	dehumidifier
so	dehumidification solution	E	evaporative cooler
sc	solar collector	R	regenerator

2. Methods

Each component's model in the LDD-RIEC system is established separately and then integrated based on the inlet and outlet relationship of parameters to facilitate the system simulation. The main components' models (LDD, RIEC and solar collector) are briefly introduced as follows.

A one-dimensional finite difference model was employed for dehumidifier/regenerator analysis. The heat and mass transfer process follows the energy and mass conservation equations, listed as follows:

1) Mass conservation equation

$$m_{f,D} d\omega_f + dm_{so} = 0 \tag{1}$$

2) Energy conservation equation

$$m_{f,D} di_f + d(i_{so} m_{so}) = 0 \tag{2}$$

3) Sensible heat exchange equation

$$m_{f,D}c_{\mathrm{pa}}dt_f = h_f(t_{\mathrm{so}} - t_f)dA \tag{3}$$

4) Overall heat exchange equation

$$m_{f,D}di_f = h_{mf}[(i_{\mathrm{sat}} - i_f) - (1 - \frac{h_f}{h_{mf}c_{\mathrm{pa}}})c_{\mathrm{pa}}(t_{\mathrm{so}} - t_f)]dA \tag{4}$$

The specific thermal capacity of lithium chloride (LiCl) solution is the function of solution temperature and solution mass fraction, calculated according to the reference [1].

The model of RIEC is established based on the energy and mass balance in the two channels, listed as follows:
1) Heat balance of secondary air

$$h_s(t_w - t_s)dA = c_{pa}m_{s,E}dt_s \tag{5}$$

2) Mass balance of secondary air

$$h_{ms}(\omega_{sat} - \omega_s)dA = m_{s,E}d\omega_s \tag{6}$$

3) Heat balance of primary air

$$h_f(t_f - t_w)dA = c_{pa}m_{f,\mathrm{E}}dt_f \tag{7}$$

4) Mass balance of evaporation water film

$$dm_{ew} = m_s d\omega_s \tag{8}$$

5) Overall energy balance equation

$$m_s di_s - c_{pa}m_{f,E}dt_f = d(c_{pw}t_{ew}m_{ew}) \tag{9}$$

6) The mass flow rates of primary air and secondary air satisfy the relationship:

$$m_s = r_2 \cdot m_{f,E} \tag{10}$$

The mass transfer coefficient (h_{ms}) can be obtained by assuming Lewis relationship is satisfied and Lewis number is unity in air-water interacted surface. The above governing equations can be written in standard ordinary differential equations and solved by finite difference method (FDM) using MATLAB tool box.

Based on the mass balance of desiccant dehumidification and regeneration process, the air moisture loss in the dehumidifier equals to the air moisture addling in the regenerator.

$$m_{f,D}\left(\omega_{f,D,in} - \omega_{f,D,out}\right) = m_{f,\mathrm{E}}\left(\omega_{f,\mathrm{E},out} - \omega_{f,\mathrm{E},in}\right) \tag{11}$$

The heat captured by the solar collector is influenced by the solar radiation, thermal property of the collector and ambient temperature. The efficiency of evacuated tube solar collectors is calculated as follows [2] .

$$\eta_{sc} = 0.84 - \frac{2.02(t_m - t_{amb})}{I} - 0.0046(\frac{t_m + t_{amb}}{2})^2 \tag{12}$$

Where t_m is the mean temperature of inlet and outlet circulated water, °C; t_{amb} is the ambient temperature, °C.Before simulation, geometrical parameters of various system components and weather data were input to the model. Totally, the LDD-RIEC consists of three calculation loops. The liquid desiccant loop in regenerator and dehumidifier and heating water in solar water system are closed-loops while the fresh air handling process is open-loop. The simulation started from the solar collector. The total heat captured by the solar collector is set as the input to HE2. Initial values were required as a starting point for the closed-loop simulation of dehumidifier and regenerator. The closed-loop simulation started from the initial values of inlet solution concentration and temperature of humidifier, which were then updated by the sub-models for the heat exchangers, cooling tower, regenerator and overall moisture balance. Once the above equations were satisfied, the final operating values of solution concertation, solution temperature, outlet air temperature and humidity can be obtained. The detailed parameters used in the simulation are listed in Table 1.

Table 1. Parameters of main components

Component	Parameter	Value
Solar collector	Solar collector gross area	50m^2
	Absorber area to gross area ratio	0.7
	Absorber efficiency	0.96
	Total thermal loss coefficient	1.2W/ m^2·°C
	Heating water flow rate	0.2kg/s
Dehumidifier/Regenerator	NTU	2.0
	Desiccant flow rate	0.2kg/s
	Air flow rate	0.1kg/s
	Inlet air temperature and humidity	30°C, 20g/kg
Cooling tower	Efficiency	0.46
	Cooling water flow rate	0.2kg/s
RIEC	Channel pairs	25
	Height × width	1.0m×0.5m
	Channel gap	4mm
	Extraction ratio (r_2)	0.3

3. Results

3.1 Influence of solar collector area

Figure 2 shows the influence of solar collector area on moisture removal rate. It can be seen that the moisture removal rate of fresh air increases from 0 to 12g/kg with the solar collector area increases from 0 to 50m^2. The increase trend becomes insignificant when the solar collector is larger than 50 m^2. The regeneration driving force increases with the inlet solution temperature. Larger solar collector area results in higher solution temperature in regenerator. Thus, more water in the weak solution can be removed and stronger solution can be produced for dehumidifier. However, the solubility of lithium chloride is limited. The lithium chloride would likely to precipitate when the mass fraction is higher than 45%. That is why the moisture removal rate remains almost steady when the solar collector increases to a certain level.

Figure. 3 shows the influence of solar collector area on the solution of LDD and air of RIEC. It can be seen from Figure 3(a) that the mass fraction of LiCl increases from 18.8% to 44.8% when the solar collector area increases from 5m^2 to 50 m^2. The inlet solution temperature of dehumidifier and regenerator also increase linearly. Larger solar collector area would bring higher moisture removal rate and higher outlet air temperature of dehumidifier as shown in Figure 3(b). The RIEC cooling capacity is largely influenced by the inlet air humidity and temperature. The lower humidity results in larger the cooling capacity, but higher inlet temperature results in higher supply air temperature. It can be seen from Figure 3(b) that the supply air temperature decreases as the solar collector area increases. So it is the air humidity dominates the RIEC performance in the LDD-RIEC system. In sum, both the latent and sensible cooling capacities are enhanced under larger solar collector area.

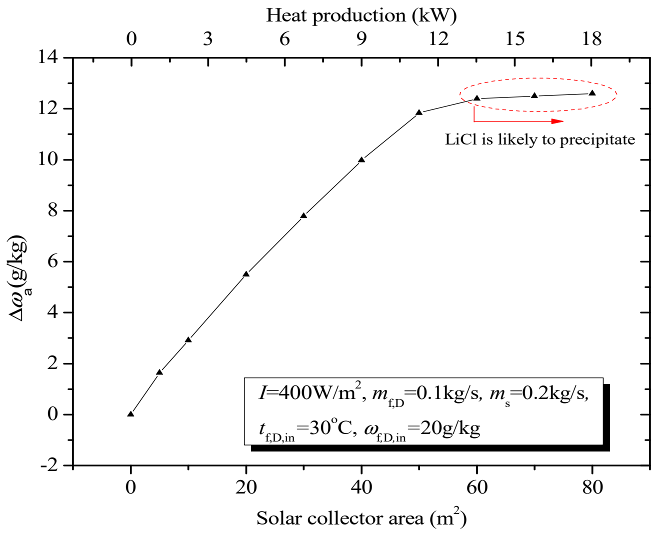

Fig. 2 Influence of solar collector area on moisture removal rate

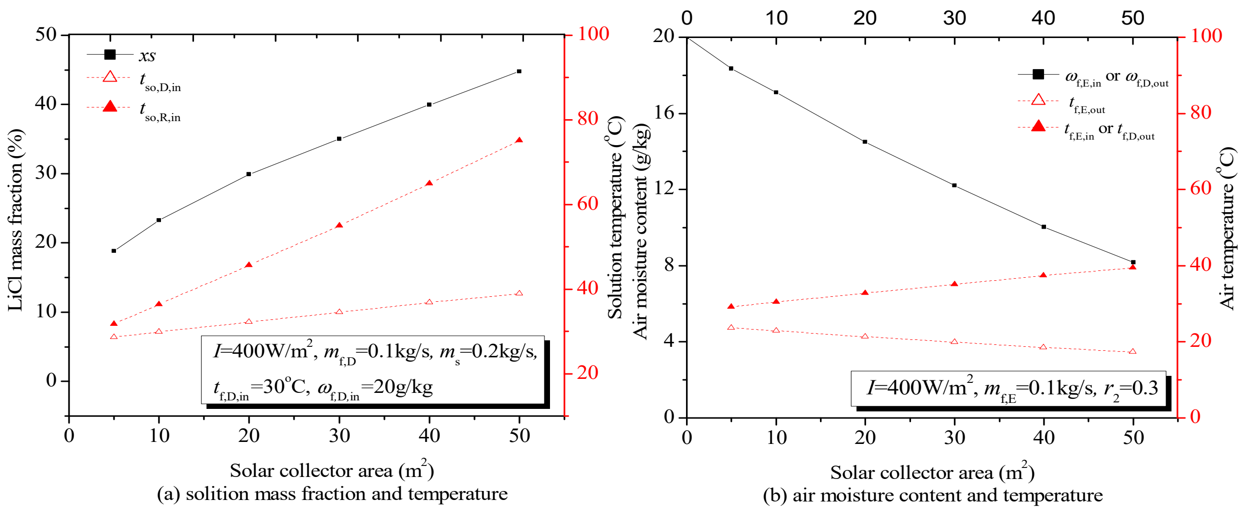

Fig. 3 Influence of solar collector area on the solution of LDD and air of RIEC

3.2 Hourly performance and energy saving potential

The performance of LDD-RIEC system is largely influenced by the weather condition. The solar radiation decides the regeneration heat source and moisture removal rate. The air temperature and humidity affect the evaporative cooling efficiency and supply air temperature. To ensure the steady performance of LDD-RIEC system, the heat storage tank and auxiliary heater are used to move the peak to fill the valley. The system hourly performance in a standard weather day of July in Hong Kong is simulated. The hourly radiation, humidity and temperature are shown in Figure 4. The operation hours of A/C system is set to be 6:00 to 21:00.

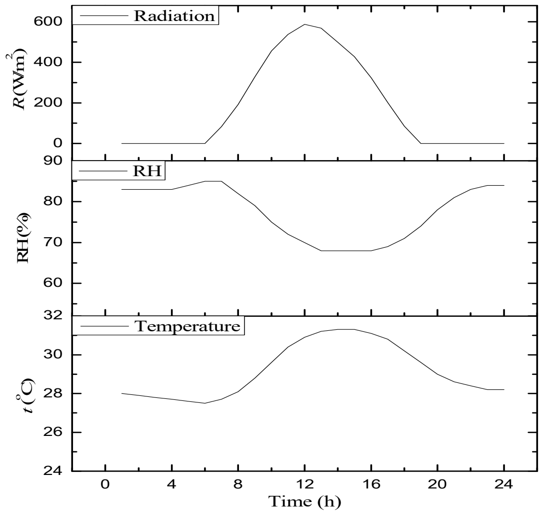

Fig. 4 Weather condition of a typical summer day in Hong Kong

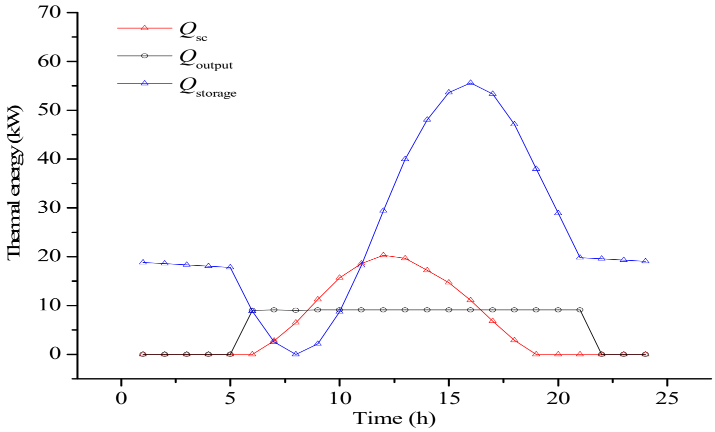

Fig. 5 Hourly thermal energy collected, storage and output

Figure 5 shows the solar energy collected, output and storage in a day. To make sure the best dehumidification effect of LDD, around 9000W thermal energy is needed for solution regeneration. As the heat collected between 9:00 to 16:00 is beyond the consumption, excess thermal energy is stored and then released in other hours when there is no solar radiation or the solar radiation is not enough. In this way, the system can operate continuously. Figure 6 shows the hourly supply air temperature and humidity to indoor. There is a little fluctuation in both supply air temperature and humidity even though the outdoor air temperature varies in a wide range. It indicates that the thermal energy input to the regenerator plays a key role in system performance. The RIEC performance not so largely depends on the outdoor air conditions because of the pre-treatment process by LDD.

The total cooling capacity provided by the LDD-RIEC system is calculated to be 15.3 kWh by assuming the indoor condition is 26 ℃ and 12.6 g/kg. The energy consumption by water pump and solution pumps are estimated to be 2 kWh. Thus, the coefficient of performance (COP) of LDD-RIEC system is 7.7, much higher than that of MVCR system which usually owns COP ranging from 3.0 to 5.0. The energy consumption of MVCR system is estimated to be 3.825 kW (COP=4) when deals with the same amount of cooling load. So 47% energy saving can be achieved by LDD-RIEC A/C system.

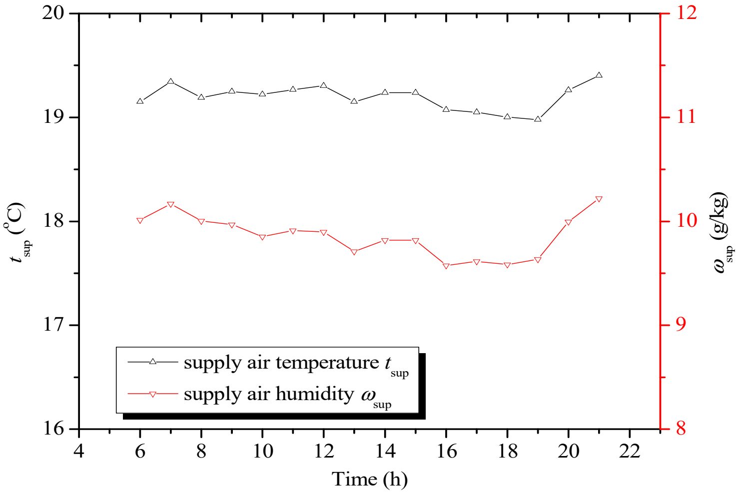

Fig. 6 Supply air temperature and humidity

4. Conclusions

The solar-assisted desiccant enhanced evaporative cooling system consisting of a liquid desiccant dehumidifier and a regenerative indirect evaporative cooler (LDD-RIEC) is proposed as a promising energy-saving air-conditioning (A/C) scheme. The system performance is analyzed by solving the heat and mass transfer equations of each component integrally in a closed loop. Simulation results show that both the moisture remove rate and cooling capacity improves with the increase of solar collector area. The LDD-RIEC A/C system saves 47% energy consumption compared with MVCR system in Hong Kong summer days.

Acknowledgements

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