EXPERIMENTAL STUDY ON SOLAR DRIVEN DEHUMIDIFICATION SYSTEM WITH SILICA GEL COATED HEAT EXCHANGER IN WINTER

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Abstract

In this paper, a desiccant coated heat exchanger (DCHE) system driven by solar energy is built and tested under winter condition. The purpose of this experimental research is to explore the heating and humidification performance of DCHE system. Effects of hot water temperature, hot water mass flow rate and regeneration air flow flux are discussed as vital factors impacting system performance. Results show that increasing of heat water temperature as well as of hot water mass flow rate both have positive effects on humidification capacity and thermal coefficient of performance (COP) of the DCHE system. Moreover, the latter has a more remarkable influence. When a tradeoff is made between the performance of DCHE system and the thermal comfort of supply air, 40oC and 0.4 kg/s are selected as optimum hot water condition. Under this operation condition, average humidity ratio of supply air is 5.15 g/kg, almost twice of ambient air. Maximum thermal COP can reach 1.78 with a comfortable average temperature of supply air (28.3 ºC). To provide a better supply air state under low humidify ratio of ambient air, small regeneration air flow flux is implemented, which effectively increases the humidity ratio of supply air with the decrease of COP.

Keywords: Silica gel coated heat exchanger, solar energy, experimental study, COP.

1. Introduction

Desiccant coated heat exchanger air conditioning system is a recently developed solid desiccant technology which obtains more and more attention in the HVAC field. Compared with vapor compression (VC) system which is widely used at present, solid desiccant system has several obvious advantages. For example, it can control both sensible and latent loads under summer and winter condition, while VC system has limited capacity in moisture control through heat pump cycle, especially cannot meet the demand of humidification in winter [1,2]. Without the use of refrigerants containing more or less CFCs which generally applied to the VC system, solid desiccant technology has an environmentally friendly property. Moreover, after the Copenhagen Conference, how to reduce building energy consumption and greenhouse gas emission has aroused unprecedented attention[3,4]. The solid desiccant air conditioning system which usually selects silica gel as desiccant provides a promising alternative solution. Since silica gel with a relative low desorption temperature can take advantage of renewable

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energy and low-grade thermal energy[5], such as solar energy and waste heat, which can be used as the regeneration heating source instead of electricity. Solid desiccant technologies possess extensive application perspective in new energy utilization and industrial commercialization.

In recent years, a novel concept of desiccant coated heat exchanger (DCHE) air condition system has been proposed and developed in solid dehumidifying. DCHE is based on the traditional fin-tube heat exchanger with the reprocessing on the out surface coated by the desiccant materials. Comparing with rotary desiccant wheel that a common equipment in solid desiccant system, DCHE is chilled by inner cooling water flowing in the copper pipes of heat exchanger, and the adsorption heat can be timely taken away in the dehumidification process. This improvement can realize the approximately isothermal dehumidification and overcome the side effect of adsorption heat accumulation due to the structure limit of rotary desiccant wheel. Therefore, DCHE system effectively enhances the moisture removal obviously which leads to a better control of the latent load. Meanwhile, there is no rotatable part in DCHE system with longer service life and less noisy in operation. Aynur et al. [6] introduced DCHE into VRV (variable refrigerant volume) air conditioning system instead of the traditional heat exchanger, and better dehumidification capacity could be achieved with less energy consumption were confirmed in the field performance test under both cooling season and heating season. Using more environmentally friendly water as working medium, Ge et al. [7] experimentally verified that DCHE could effectively handle both the sensible heat and the latent heat of process air in the dehumidification process. Further works by Zhao et al. [8] successfully introduced solar energy to drive DCHE system and used two paratactic DCHE units to provide continuous dehumidification capacity. Later, Zhao et al. [9] added internal heat recovery to build a new type of DCHE cycle and both the thermal and electrical coefficient of performance significantly increased (1.2 and 13.8, respectively), while providing better indoor thermal comfort in summer condition.

The dehumidification abilities of DCHE which is applied in summer condition have caught the main attention of scholars on no matter in experimentally or theoretically investigations. However, few researches on regeneration process of DCHE system have been done to meet the demand in winter. The main objectives of this paper are to utilize a solar powered desiccant coated heat exchanger humidification air conditioning system and to validate the heating and humidification performance under winter condition. What’s more, how the different regeneration conditions (including hot water temperature, hot water mass flow rate and regeneration air flow flux) affect the humidification process are experimented and analyzed.

2. Description of experimental system

Fig.1 shows photographic view of the experimental setup and main components. The DCHE air conditioning system consists of three main components: desiccant humidification unit, solar collecting unit and cooling unit. And its function covers humidification in winter and dehumidification in summer simultaneously.

As the core device of the system, DCHE is based on the traditional fin-tube heat exchanger, the size of which is 400 mm (length)×150 mm (width)× 400 mm (height). After being soaked by desiccant and dried for 3-5 times, the surfaces of all pipes and fins of the heat exchanger are coated. Solid silica gel with 0.15 mm particle diameters and liquid silica gel are used as the desiccant materials in the experiment. And the final glue quantity of DCHE is 2.53 kg with 0.316 kg on per square meter. The detailed structural parameters of the heat exchanger and specifications of silica gel are shown in Table 1.

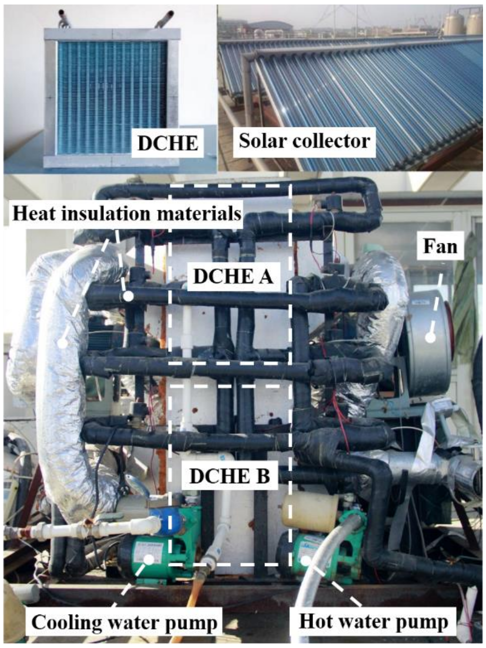


Fig.1 Photographic view of experimental setup and main components

Table 1 The structural parameters of the heat exchanger and specification of silica gel

Name	Parameter
Structural size (mm)	400 (length)×150 (width)×400 (height)
Thickness of the fin (mm)	0.15
Spacing of the fin (mm)	3
Outer diameter of the tube (mm)	9.87
Inner diameter of the tube (mm)	8.67
Silica gel column chromatography	Macro pore, ZCX- Ⅱ . JN30,30%
Particle diameters of silica gel (mm)	0.15
Glue quantity (kg)	2.53

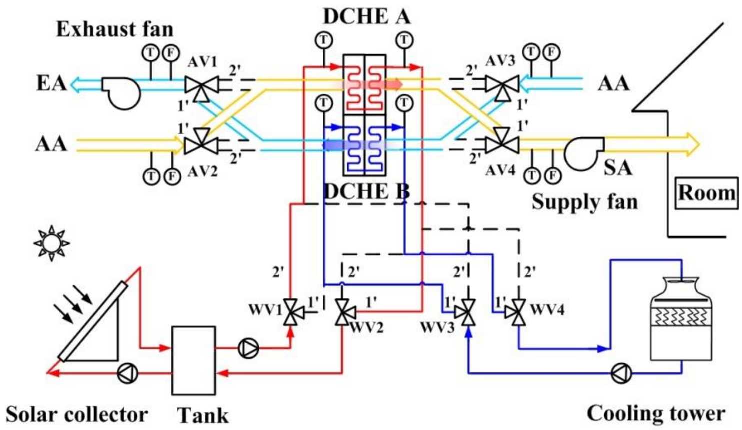
Solar energy is used as regeneration source in the experiment. The vacuum tube solar collector can supply 8.5 kW heating power with 22 m2 area. The capacity of the matched tank is 500 L. Through adjusting heating time and mass flow rate of circulating water in solar collecting unit, the temperature of hot water can meet the experiment requirements in different sunlight intensity. The cooling water after the dehumidification process flows back to cooling tower. In the cooling tower, the temperature of water decreases by air cooling.

The cooling water and hot water are dominated by two pumps in the water loops. In the experiments, the mass flow rate of cooling water is constant at 0.32k g/s. By adjusting the valve opening of the water loop, the water mass flow rate of hot water can be regulated. The maximum water mass flow rates of the cooling water and hot water provided by two pumps are 0.32 kg/s and 0.4 kg/s, respectively.

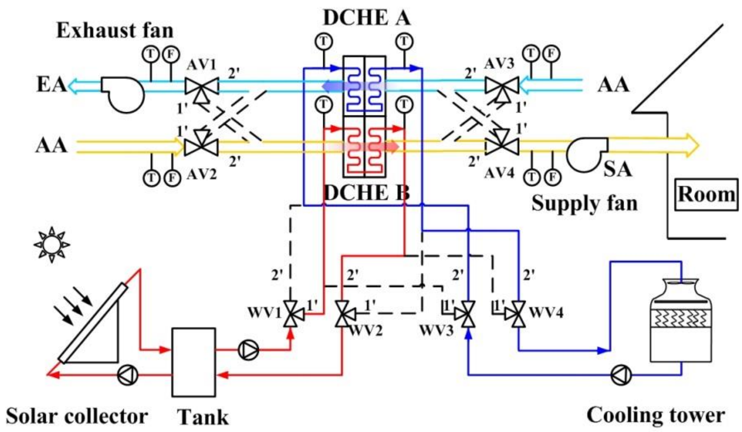
Moreover, it is extremely important to complete the airtightness and heat insulation of both air and water pipes to ensure good performance of the system. The leakage of water and air have been checked and precluded before the experiment. To minimize the heat loss, all the pipes are wrapped with heat insulation materials, including fiber-glass on air pipelines and heat insulation felt on water loop.

The basic operation principles of DCHE system consist of dehumidification process and regeneration process. In dehumidification process, ambient air (AA) is dehumidified and cooled in the air side of DCHE, by the desiccant and cooling water, respectively, then the cold dry air discharged to the environment as the exhaust air (EA). Meanwhile, the desiccant absorb moisture from the ambient air with adsorption heat taken away by cooling water and moisture content rise which is well prepared for the regeneration process. Then heat and mass transfer process between air and desiccant has basically completed in the end of dehumidification process. And cooling tower provides cooling water for dehumidification process in the system. In the following regeneration humidification process, when regeneration hot water flows into the copper pipes of DCHE, the humid desiccant coated on the heat exchanger is heated , and it enters the desorption process. As a result, the heat and moisture are taken away by ambient air (AA) which is supplied to the conditioned space with an increase of temperature and humidity ratio as supply air (SA). The sensible and latent loads of the supply air are promoted at the same time in the regeneration process. Then the desiccant become relatively dry which recovers the dehumidification capacity. And hot water in the system for the regeneration process is from solar collecting unit.

Based on above principles, the experimental setup is established, and two alternate operation modes are proposed to realize the continuous operation of the system as shown in Fig.2 (a),(b). Two DCHEs, including DCHE A and DCHE B which are installed in two paratactic air ducts, compose the desiccant humidification unit. In the MODE 1, the two water values (WV1,WV2) in hot water loop open 2' and 1' direction, respectively, which provide the regeneration water to DCHE A. The other two water values (WV3,WV4) in cooling water loop open 1' direction and pump the cooling water into the DCHE B. As a result, DCHE A operates in regeneration process, and DCHE B operates in dehumidification process. Meanwhile, the four 3-way air values open 1' direction that the cold dry AA through DCHE A is handled into hot humid SA supplied into conditioned space. In the MODE 2, the two water values (WV1,WV2) in hot water loop open 1' and 2' direction, respectively, which provide the regeneration water to DCHE B. The other two water values (WV3,WV4) in cooling water loop open 2' direction and pump the cooling water into the DCHE A. DCHE B operates in regeneration process, and DCHE A operates in dehumidification process. Meanwhile, the four 3-way air values open 2' direction. The air flowing through the surfaces of DCHE B is heated and humidified which is supplied to the conditioned space. By switching multiple 3-way water valves and air valves completing the conversion of the two modes, DCHE A and DCHE B alternately complete dehumidification and regeneration humidification process which realize the continuous hot and moist air supply.



(a)



(b)

Fig.2 Schematic diagram of the experimental setup:(a) MODE1: DCHE A in regeneration process and DCHE B in dehumidification process (b) MODE2: DCHE A in dehumidification process and DCHE B in regeneration process

3. Performance indices

Performance of DCHE humidification air conditioning system in winter is evaluated by the following indices:

(1) Supply air state(T_t, d_t, T_{ave}, d_{ave})

The temperature and humidity ratio of supply air are the primary criterion to judge whether the system can achieve the required heating and humidification capacity in winter condition.

Among them, transient temperature T_t and transient humidity ratio d_t indicate the change regularity of supply air state in each cycle. And during the humidification process t_e, the average temperature T_ave and humidity ratio d_ave are another two important indices to assess the performance of the whole system. And they are expressed as following Eq. (1) and Eq. (2), respectively:

$$T_{ave} = \overline{\sum_{0\to t_e} T_t} \tag{1}$$

$$d_{ave} = \overline{\sum_{0\to t_e} d_t} \tag{2}$$

(2) Average moisture addition (Δd_{ave})

Δd_{ave} is the most intuitive parameter adopted to evaluate the capacity of humidification of the system, which is expressed by average moisture adding of supply air in per cycle as the following Eq. (3):

$$\Delta d_{ave} = \overline{\sum_{0\to t_e} \Delta d_t} = \overline{\sum_{0\to t_e} (d_t - d_{in})} \tag{3}$$

where Δd_t is transient moisture addition, d_{in} and d_t are humidity ratio of inlet air and outlet air in regeneration process, respectively in g/kg.

(3) Thermal coefficient of performance(COP)

The energy utilization of the system is measured by COP, which is the ratio of Q_t and Q_w. Q_t is the average enthalpy exchanged of process air in effective dehumidification process, and Q_w is the average enthalpy exchanged of water in effective regeneration process, respectively in kW.

$$COP = \frac{Q_t}{Q_w} = \frac{M_a\left(h_{a,out} - h_{a,in}\right)}{c_w M_w\left(T_{w,in} - T_{w,out}\right)} \tag{4}$$

where M_a and M_w are mass flow rate of air and hot water, respectively in kg/s. h is the enthalpy in kJ/kg. $T_{w,in}$ and $T_{w,out}$ are inlet and outlet temperature of hot water, respectively in K. c_w is the specific heat of water in kJ/(kg·K).

4. Results and discussions

The solar powered DCHE humidification air conditioning system is tested to evaluate the feasibility of heating and humidification in the typical winter condition from 15 December 2015 to 31 January 2016 in Shanghai. And the system performances are compared and discussed based on three crucial regeneration factors, including hot water temperature $T_{w,in}$, hot water mass flow rate m_w and regeneration air flow flux V_a. Because the thermo-hygrometric condition of the environment air changed every day, even unstable from day to night. Based on a great deal of experiments, the data is selected and compared with the principle of a single variable. Besides, 600 s is recommended as the experiment cycle in order to guarantee the experiment performance.

4.1 Effect of hot water temperature

The temperature of hot water has an important influence on the regeneration process of DCHE and makes a further effect on the humidity and temperature of supply air. To explore how the hot water temperature affect the performance of the system, the test water temperatures are specified at 30, 35, 40 and 45 °C. In addition, the humidity ratio of ambient air is around 2.91 g/kg-3.10 g/kg, the hot water mass flow rate and regeneration air flow flux are 0.4 kg/s and 400 m^3/h, respectively. These three parameters remain constant under this test condition.

The transient humidity ratio of supply air under different hot water temperature is shown in Fig.4. There is an obvious increase of moisture content under every condition compared with ambient condition, which demonstrates that the solar powered DCHE humidification air conditioning system can effectively improve the air humidity ratio in winter condition.

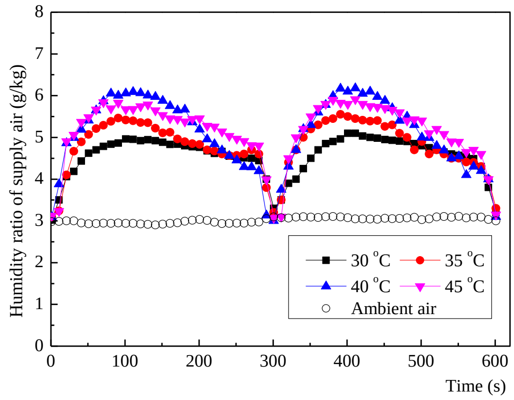


Fig.3 The transient humidity ratio of supply air with different hot water temperatures

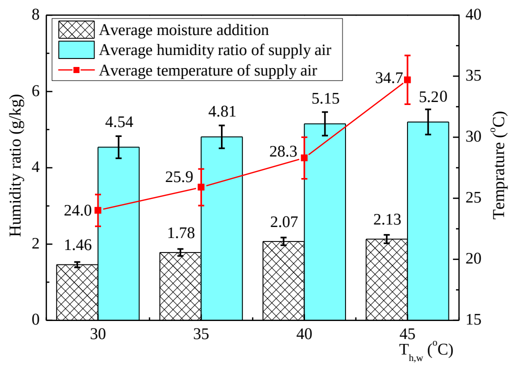


Fig.4 The average moisture addition, humidity ratio and temperature of supply air with different hot water temperatures

With the rising of $T_{w,in}$, the transient and average humidity ratio of supply air both increase as shown in Fig.3 and Fig.4. And the average value increases from 4.54 g/kg to 5.20 g/kg, up 15 %. The average moisture addition rises from 1.46 to 2.13, up 46%. Due to higher hot water temperature for desiccant material more heating power and humidification capacity can be obtained, then the regeneration process is completed thoroughly, which directly leads to the increase of moisture addition and humidity ratio of supply air. On the other hand, the surface of solid desiccant becomes drier at the end of the regeneration process with the rising of $T_{w,in}$, which increases the moisture removal and indirectly accelerates the next regeneration process. As it shows in Fig.4, the temperature of supply air rises from 24.0 °C to 34.7 °C due to the increment of the temperature difference between hot water and air/desiccant. And the slope of the curve is elevated. Through analyzing the above variation trends, the increase of $T_{w,in}$ has more effect on the rise of sensible load than latent load in the test condition which reflects on the tendencies of temperature and humidity ratio of supply air, respectively. At the same time, COP increases from 1.05 to 1.85, up 76 %, which increases obviously from 30 °C to 35 °C, then gradually become flat when from 35 ºC to 45 ºC.

Transient supply air states in one cycle are plotted in the psychrometric figure(Fig.5) to measure whether the system can provide satisfied supply air under test condition. The black solid dot represents ambient air state, area circled by blue dashed lines show the designed standard of indoor air in winter China (temperature: 18 ºC-24 ºC, relative humidity ratio: 30 %RH-60 %RH)[24] []and the hollow points are the supply air state under different hot water temperatures. It is found that the supply air states gradually enter the designed standard area with the temperature increase from 30 ºC to 40 ºC. However, the supply air states is far from the area when $T_{w,in}$, is 45 ºC, mainly because the temperature of supply air is too high(the average temperature of supply air is 34.7 ºC). To balance the performance of the system and the thermal comfort of supply air, in spite of the performances of system (including d_{ave}, Δd_{ave}, COP) best in 45 ºC, 40 ºC is selected as the appropriate hot water temperature whose average humidity ratio is 5.15 g/kg, average temperature is 28.3 ºC , average moisture addition is 2.07 and COP is 1.78.

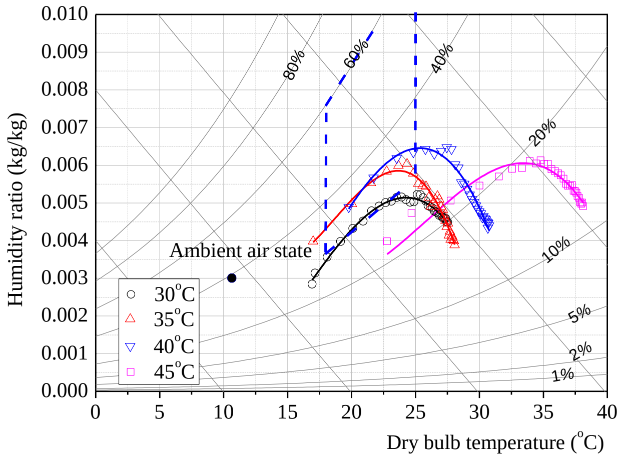


Fig.5 Transient supply air states in psychrometric figure with different hot water temperatures

4.2 Effect of hot water mass flow rate

In the solar powered DCHE system，the hot water flowing in the DCHE provides the desorption heat in regeneration process. The mass flow rate of hot water directly affects the heat exchanger efficiency between air and water, and crucially impacts the humidification and heating performance of the system. In order to explore the effect of m_w, the system is tested under constant condition that the humidity ratio of ambient air is around 2.42 g/kg-2.59 g/kg, the hot water temperature is 40 ºC and regeneration air flow flux is 400 m^3/h. Through adjusting the valve opening of the hot water loops, the different mass flow rates of hot water are controlled to 0.1, 0.2, 0.3, 0.4 kg/s, respectively. And the transient and average experimental results are summarized in Fig.6-9. In Fig.6, when the mass flow rate of hot water is greater than or equal to 0.2 kg/s, transient humidity ratio of supply air first rapidly increases to a maximum value and then gradually falls down. In the beginning period, there is a bigger relative humidity ratio difference between ambient air and pores within desiccant material, which acts as the main driving force for mass transfer and brings in the increase of moisture addition. However, water in desiccant material is limited, which is the main reason why the humidity ratio of supply air decreases in the following process. But when mass flow rate of hot water is 0.1 kg/s, the variation trend is different. Transient humidity ratio of supply air increases in the beginning and then becomes flat without a drop process. This phenomenon occurs because the mass flow rate (0.1 kg/s) is too small to provide enough desorption heat in regeneration process and the regeneration process proceeds slowly which has not yet emerged the obvious influence due to the water decrease in desiccant material.

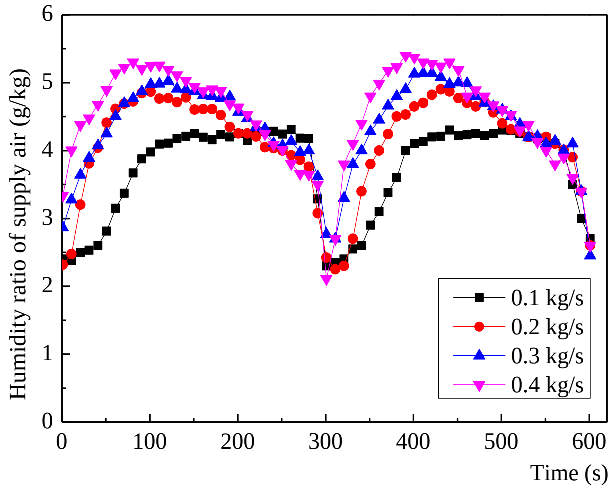


Fig.6 The transient humidity ratio of supply air with different hot water mass flow rate

With the increase of mass flow rate of hot water from 0.1 kg/s to 0.4 kg/s, all the performance indices are enhanced. Average humidity ratio of supply air, moisture addition and COP have approximately linear rises, up 24 %, 71 % and 102 %, respectively. And the increase trend of average temperature differs from others, which is from sharp to flat. This phenomenon indicates that the effect of hot water flow mass on the supply air temperature weaken when it is above 0.2 kg/s. Comparing with hot water temperature(up 15 %, 46 %, 76 %, respectively), mass flow rate of hot water has a greater influence on system performance indices when other parameters remain the same.

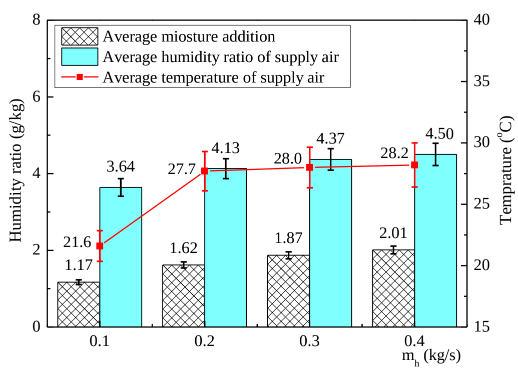


Fig.6 The average moisture addition, humidity ratio and temperature of supply air with different hot water mass flow rate

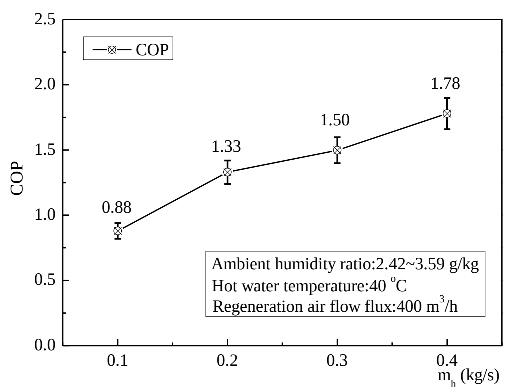


Fig.7 The average COP of the system with different hot water mass flow rate

Except for the performance of system, the thermal comfort of supply air also needs to be taken into account. Fig.8 shows the transient supply air states in psychrometric figure with different mass flow rate of hot water. When mass flow rate of hot water increases, the curves moves towards the upper right of the figure due to the promotion of heating and humidification performance. Compared with the experimental results of 0.1, 0.2, 0.3 kg/s, more points of supply air curve in 0.4 kg/s are included in the designed standard of indoor air, which can provide more comfortable temperature and humidity ratio to the conditioned space.

To sum it up, the maximum hot water mass flow rate (0.4 kg/s) is recommended in this system in order to improve regeneration process and provide better supply air condition.

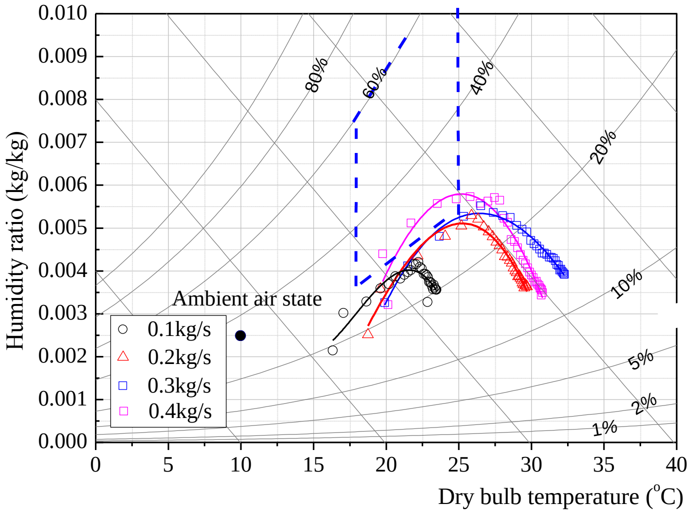


Fig.8 Transient supply air states in psychrometric figure with different hot water mass flow rate

5. Conclusion

In this paper, the solar powered DCHE air conditioning system is established and tested to research the humidification performance of DCHE in winter condition. Three important factors impacting regeneration process are discussed. The main conclusions are as follows:

(1)Experimental results of supply air humidity ratio validate that DCHE system possessed a good humidification and heating performance in winter condition.

(2)Under a single variable, humidification capacity and COP of DCHE system have a prominent increase with the rising of heat water temperature, as well as hot water mass flow rate. And through analysis of results, mass flow rate has a greater influence on all performance indices of the system than water temperature.

(3)To balance the performance of the system and the thermal comfort of supply air, 40 °C and 0.4 kg/s are optimum temperature and mass flow rate of hot water, respectively. And the best operation state of the system in this hot water condition is concluded that average humidity ratio of supply air is 5.15 g/kg, average temperature of supply air is 28.3 °C and COP is 1.78.

6. ACKNOWLEGEMENT

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