# Experimental study of dynamic characteristics of liquid desiccant dehumidification processes

Lingshi Wang[1], Fu Xiao[1,*], Xiaofeng Niu[2], and Dian-Ce Gao[1]

[1]Department of Building Services Engineering, The Hong Kong Polytechnic University, Kowloon, Hong Kong

[2] College of Urban Construction, Nanjing Tech University, Nanjing 210009, China

*****Corresponding author. Tel.: +852 2766 4194; Fax: +852 2765 7198.

*E-mail address*: linda.xiao@polyu.edu.hk

## ABSTRACT

Liquid desiccant dehumidification is an effective method of removing moisture from the air for air conditioning in built environments. The dehumidifier is a critical component where coupled heat and mass transfer between the desiccant solution and the air occurs. Understanding the dynamic characteristics of the dehumidifier is essential to develop controllers and operation strategies for the liquid desiccant hybrid air conditioning systems. This paper presents an experimental study of the dynamic heat and mass transfer characteristics of a counter-flow packed-type liquid desiccant dehumidifier. Experiments were carried out to investigate the dynamic responses of the outlet air and desiccant solution to various changing inlet conditions. In addition, the influences of typical configuration and operation parameters on the dynamic dehumidification process were analyzed. The results indicate that the settling time of the dynamic process decreases with the air and solution flow rates while increases with the packing height. The experimental results also show that the outlet air humidity ratio stabilizes sooner than the outlet air temperature during the dynamic process. The time constants of the heat and mass transfer processes were obtained, which are valuable to controller design.

*Keywords*: Liquid desiccant; Dynamic characteristics; Time constant; Experimental study; Parameter analysis

## Introduction

Air dehumidification is an important and energy-intensive air conditioning process for creating comfortable built environments. Traditionally, the supply air is dehumidified by condensation at a low temperature, which consumes a significant amount of energy, particularly in humid areas. Liquid desiccant dehumidification is an effective alternative method, which uses the strong desiccant solution to directly absorb moisture from the air. It can achieve more effective humidity control at lower energy cost (Liu et al. 2006a; Niu et al. 2010). Due to the separate treatment of the sensible and latent loads, independent control of the indoor temperature and humidity in the built environments is feasible and reliable using the liquid desiccant hybrid air conditioning systems (Zhu et al. 2010). In recent years, a diversity of liquid desiccant hybrid air conditioning systems have been developed, such as the hybrid systems with heat pump (Abdel-Salam et al. 2014a; Bergero and Chiari 2011; Lazzarin and Castellotti 2007; Zhang et al. 2012), evaporative cooler (Yin et al. 2007) and dedicated outdoor air system (Xiao et al. 2011). Meanwhile, commercial products of those hybrid systems are emerging (Zhu et al. 2010; Lazzarin and Castellotti 2007; Ma et al. 2006). A comprehensive review on the liquid desiccant air conditioning technologies was conducted by Abdel-Salam and Simonson (2016). The dehumidifier is one of the main components in the liquid desiccant systems, whose performance is critical to the overall system performance. Substantial experimental studies have been conducted to understand the complicated heat and mass transfer process occurring in the dehumidifier (Yin et al. 2014; Mohammad et al. 2013). The experimental studies are highly valued which provide reliable data for validating the theoretical models, and empirical correlations for determining model parameters, such as the mass transfer coefficient (Yin et al. 2014).

Most of the experimental studies focus on the performance of the dehumidifier at steady states. Fumo and Goswami (2002) studied the heat and mass transfer processes in a random packed-type dehumidifier and regenerator. The performance of the dehumidifier and the regenerator was assessed under different inlet parameters of the air and the desiccant solution. The heat and mass transfer in a dehumidifier/regenerator with random packing was studied experimentally and theoretically by Longo and Gasparella (2005). The air humidity reductions under different mass flow rate ratios between the desiccant and the air were obtained by experiments with different desiccants. A liquid desiccant evaporation cooling air conditioning system was established by Yin et al. (2007). The empirical correlations of the dehumidification rate in the dehumidification process and the mass transfer coefficient in the regeneration process were obtained. Zhang et al. (2010) investigated the mass transfer characteristics of a dehumidifier and a regenerator with the cross flow structured packing and developed the dimensionless correlations for the overall mass transfer coefficients of the dehumidification and regeneration processes. Liu et al. (2006b) conducted a parameter analysis to study the moisture removal rate and the dehumidification effectiveness of a cross flow dehumidifier. The empirical correlations of the enthalpy and the moisture effectiveness of the cross flow dehumidifier were also proposed by Liu et al. (2006a). Jain and Bansal (2007) summarized the empirical correlations of the mass transfer coefficient and the dehumidification effectiveness reported by previous researchers. A comprehensive comparison using these empirical correlations was conducted to analyze the performance of packed-type dehumidifiers. In addition, the membrane technology has been used in the indirect-contact liquid desiccant dehumidifier/regenerator and energy recovery ventilators, and has attracting much attention in recent years (Abdel-Salam et al. 2014b; Ge et al. 2013; Woods, 2014).

Only few studies pay attention to the performance of the dehumidifier at unsteady states. Peng and Pan (2009) conducted a transient heat and mass transfer experiment in a liquid desiccant dehumidifier with random packing to validate the proposed model of the dehumidification process. However, the authors only considered the dynamic performance of the dehumidifier under the working condition of a low desiccant flow velocity. In real applications, the desiccant flow velocity are often much larger than that in Peng and Pan (2009). Bakhtiar et al. (2012) proposed a new COP (coefficient of performance) formula to evaluate the performance of the liquid desiccant dehumidification system at the unsteady state. The experimental results reveal how the moisture removal rate and the effectiveness change over time. This new COP formula is proved more suitable for the performance evaluation of the liquid desiccant dehumidification system at the unsteady state when compared with the conventional methods. Namvar et al. (2012) experimentally investigated the transient and steady states effectiveness of a liquid to air membrane energy exchanger (LAMEE) consisting of semi-permeable membranes. Magnesium chloride solution was used as the desiccant solution. The experimental data was fitted by the exponential correlations with two time constants to describe the transient response of the outlet air. The experiment also showed that the effectiveness and the single time constant of the LAMEE are significantly influenced by the air and desiccant flow rates. A solar-driven parallel plate liquid desiccant air conditioning (LDAC) system was installed at Queen's University, the transient inlet and outlet conditions of the dehumidifier as well as the hourly energy of the system during a test day were presented (Crofoot and Harrison, 2012). Similar field tests were conducted in an internally cooled/heated liquid desiccant air conditioning system (Abdel-Salam et al., 2016). The transient and quasi-steady performance were compared and they have good agreement except during the start-up stage. The average data for transient field tests can be used to predict the quasi-steady performance of the LDAC system.

In the practical applications, the liquid desiccant hybrid air conditioning systems work under changing conditions due to the time varying inlet conditions. The dynamic characteristics of the dehumidifier is critically important to design and tune real-time controllers, and develop operation strategies for the hybrid systems. Substantial experimental studies have been conducted on the dynamic characteristics of conventional air-conditioning components, such as, energy wheel (Abe et al. 2006), heat exchanger (Lachi et al. 1997; Diaz et al. 2001), cooling tower (Marques et al. 2009), cooling coil (Jin et al. 2006), air-conditioning room (Yao et al. 2013; Zhang et al. 2015), etc. However, the experimental study on the dynamic operating characteristics of a liquid desiccant dehumidifier is very limited at present. This study conducts experimental study on the dynamic heat and mass transfer characteristics of the dehumidifier under various operating conditions. The packed-type structure with counter flow pattern is used as the configuration of the dehumidifier which provides more contact area between the air and the desiccant. A comprehensive experimental facility for the packed-type dehumidifier has been established. Experiments are conducted to study the dynamic behaviours of dehumidification processes in the dehumidifier under various transient conditions including at the beginning of a dehumidification process and step change of inlet parameters. The influence of one configuration parameter (i.e., the height of the packing) and two operation parameters (i.e., the air flow rate and the solution flow rate) are further investigated by the parameter analysis method.

## Experimental facility

### *Dehumidification test rig*

An experimental facility has been built to study the dynamic characteristics of the dehumidification processes in a liquid desiccant dehumidifier. The schematic of the experimental facility is shown in Fig.1. Fig.2 shows the photograph of the experimental facility. In this liquid desiccant dehumidification test rig, the dehumidifier is the key component. This dehumidifier utilizes the packed tower structure with the shell of 8mm acrylic plastic glazing for good thermal insulation with the environment. The packing has a good wettability since it is made of cellulose fiber paper with porous structure. The dimensions and specific surface area of the packing are shown in Table 1. The height of the packing is 0.4m and can be adjusted in experiment tests.

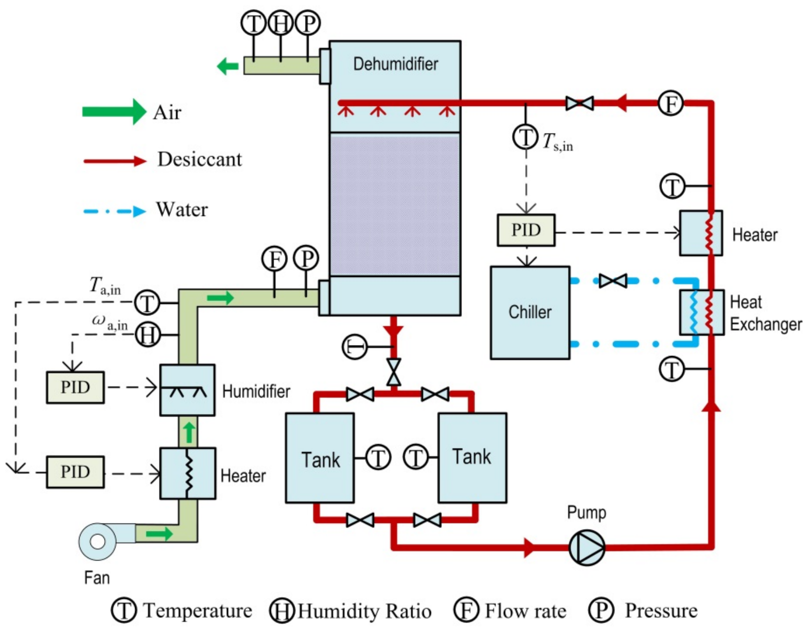


Fig. 1. Schematic of experimental facility.

An electric heater and an electrode humidifier are installed in the air duct. Through proper controls, the air is heated and humidified in the duct until reaching the desired temperature and humidity. Then, the air goes through the dehumidifier from bottom to top. In this study, lithium chloride (LiCl) aqueous solution is used as the liquid desiccant. There are two desiccant storage tanks, which are cuboid with the same size, 0.4m in height, 0.5m in length and 0.4m in width. The desiccant is stored in one of the two tanks. In order to obtain the required temperature, the desiccant solution, pumped by a fluorine-lining magnetic pump, is cooled or heated by a plate heat exchanger and an electric heater. The cooling water in the heat exchanger is generated by a chiller. The specifications of the heaters, the humidifier and the chiller are summarized in Table 1. When the air and desiccant reach the desired conditions, the desiccant solution then flows into the dehumidifier.

Two spray pipes (each with ten holes below) and a porous plate are used for uniform distributions of the desiccant over the packing. The strong solution exchanges heat and mass with the air in the dehumidifier. Then, the diluted desiccant solution flows into another tank.

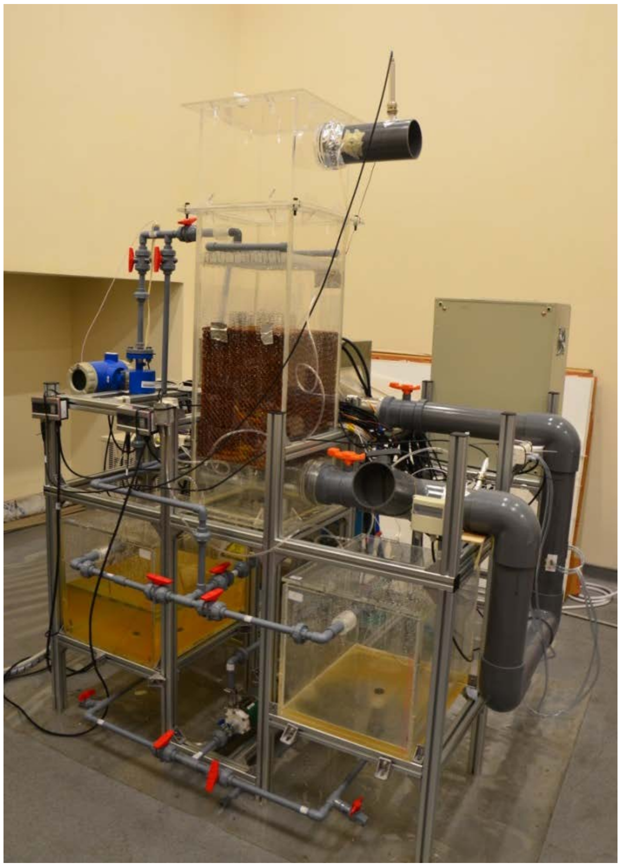

Fig. 2. Photograph of experimental facility.

Table 1. Specifications of packing and electric equipment in the experimental facility.

| Device | Range |
|---|---|
| Height of packing (m) | 0.3-0.5 |
| Width of packing (m) | 0.3 |
| Length of packing (m) | 0.3 |
| Specific surface area of packing ($m^2/m^3$) | 650 |
| Heating power of solution heater (kW) | 4 |
| Heating power of air heater (kW) | 4 |
| Humidifying capacity of air humidifier (kg/h) | 4 |
| Cooing capacity of chiller (kW) | 2.7 |

## *Measurement system*

The inlet and outlet conditions of the air and the desiccant are measured during the experiments. The temperatures of the air and the desiccant solution are measured by fast-response type temperature sensors (PT100 RTDs ($\Phi$2mm)). Two humidity transducers are used to measure the inlet and outlet air humidity ratios. The flow rates of the air and the desiccant solution are measured by a differential pressure flow meter and an electromagnetic flow meter, respectively. The density of the desiccant solution is measured by a specific gravity hydrometer. The concentration of desiccant solution can be calculated using the measured solution temperature and density based on the fitting formulas reported by Conde (2004). Other thermophysical properties of LiCl aqueous solution are also referenced from Conde (2004). The specifications of the main measuring instruments in the experimental facility are listed in Table 2.

Two temperature PID controllers are employed for maintaining the temperatures of the inlet air and desiccant at constant set-points respectively. Similarly, a humidity PID controller is utilized for maintaining the inlet air humidity at a constant set-point. All the PID controllers and switches of electric equipment are centralized into a control cabinet. Besides, the chilled water temperature is also maintained at a constant set-point by an internal PID controller in the chiller. All the measured data are collected in the data acquisition unit (Agilent 34972A).

Table 2. Specifications of measuring instruments.

| Device | Type | Accuracy | Range |
|---|---|---|---|
| Thermometer | PT100 RTD | ±0.1 $^{o}$C | -50-200 $^{o}$C |
| Humidity transducer | HF535-W, HC2-S3 | ±0.8%RH; ±0.1$^{o}$C | 0-100%RH; -40-100 $^{o}$C |
| Solution flowmeter | LDE-15 electromagnetic flowmeter | ±0.5FS | 0.06-6.36m$^3$/h |
| Air flowmeter | CP218-BO differential pressure flowmeter | ±2% | 0-30m/s |
| Densitometer | Specific gravity hydrometer | ±1kg/m$^3$ | 1000-1400kg/m$^3$ |
| Pressure transmitter | QH-800-FYair pressure gauge | ±0.25%FS | 0-500Pa |

In order to verify the measurement accuracy of the measuring system and the adiabatic condition of the dehumidifier, the energy and mass balance analysis under steady state conditions are conducted.

The enthalpy variations of the air and the desiccant flow through the dehumidifier can be determined by Eqs. (1) and (2), respectively:

$$Q_{\mathrm{a}} = m_{\mathrm{a}}(h_{\mathrm{a,in}} - h_{\mathrm{a,out}}) \tag{1}$$

$$Q_{\mathrm{s}} = m_{\mathrm{s,out}} h_{\mathrm{s,out}} - m_{\mathrm{s,in}} h_{\mathrm{s,in}} \tag{2}$$

where, the outlet mass flow rate of the desiccant solution ($m_{\mathrm{s,out}}$) can be determined by Eq.(3).

$$m_{\mathrm{s,out}} X_{\mathrm{s,out}} = m_{\mathrm{s,in}} X_{\mathrm{s,in}} \tag{3}$$

Combining Eq.(2) and Eq.(3), the enthalpy variation of the desiccant can be obtained by Eq.(4).

$$Q_{\mathrm{s}} = \left( \frac{X_{\mathrm{s,in}}}{X_{\mathrm{s,out}}} h_{\mathrm{s,out}} - h_{\mathrm{s,in}} \right) m_{\mathrm{s,in}} \tag{4}$$

The mass variation of the air, i.e. the moisture removal rate of the air is calculated by Eq. (5).

$$m_{\mathrm{de}} = m_{\mathrm{a}} (\omega_{\mathrm{a,in}} - \omega_{\mathrm{a,out}}) \tag{5}$$

The mass variation of the desiccant solution is calculated by Eq. (6).

$$\Delta m_{\mathrm{s}} = m_{\mathrm{s,out}} - m_{\mathrm{s,in}} = \left( \frac{X_{\mathrm{s,in}}}{X_{\mathrm{s,out}}} - 1 \right) m_{\mathrm{s,in}} \tag{6}$$

The mean deviation (*MD*) is used to evaluate the adiabatic condition:

$$MD = \frac{1}{N} \sum_{i=1}^{N} \frac{|\theta_{\mathrm{a}} - \theta_{\mathrm{s}}|}{\theta_{\mathrm{a}}} \tag{7}$$

where, $\theta$ represents either enthalpy variation or mass variation.

Fig.3 shows the energy and mass balance between the air and the desiccant solution under the steady state conditions. The results show that almost all deviations are less than ±15%. The mean deviations (*MD*) are 7.7% for the energy balance and 9.4% for the mass balance, which indicates that measurement accuracy and the adiabatic condition are well satisfied for the experiment.

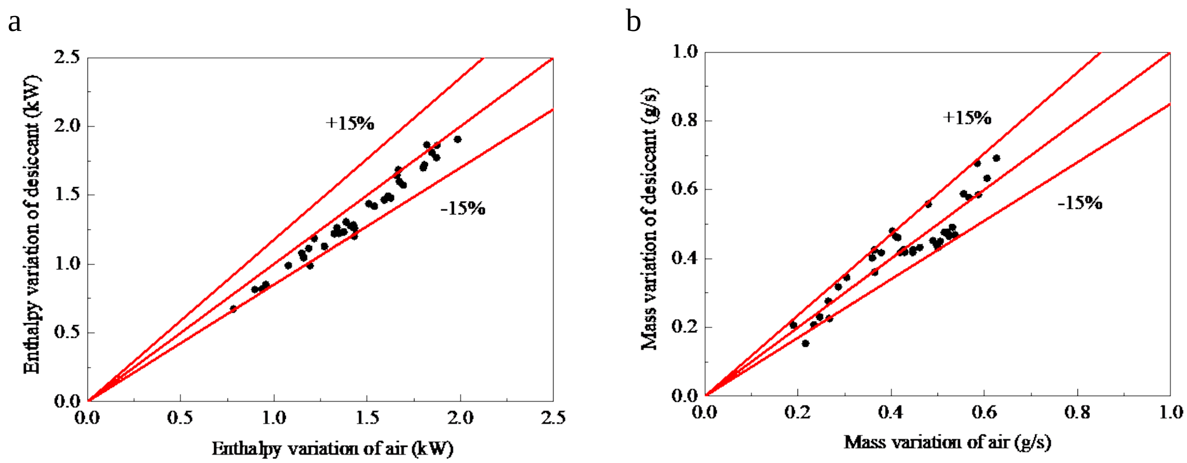


Fig. 3. Energy and mass balance analysis between air and desiccant solution: (a) energy balance, (b) mass balance.

## Experiment results and discussions

In this study, the dynamic heat and mass transfer characteristics of the dehumidifier are investigated by two types of transient conditions: at the beginning of a dehumidification process and the step change of the inlet air humidity ratio or the solution flow rate. The inlet air and solution conditions created for the tests are listed in Table 3.

Table 3. Experimental inlet conditions of air and desiccant solution.

| Figure | Air | | | Desiccant solution | | |
|---|---|---|---|---|---|---|
| | $m_a$ (kg/s) | $T_a$ (ºC) | $\omega_a$ (g/kg) | $m_s$ (kg/s) | $T_s$ (ºC) | $X$ (%) |
| Fig.4 | 0.079 | 30.0 | 16.7 | 0.114 | 21.2 | 35.8 |
| Fig.5 | 0.057 | 30.0 | 17.5-13.8-16.0-14.1 | 0.095 | 24.3 | 35.0 |
| Fig.6 | 0.064 | 30.0 | 16.5 | 0.048-0.098-0.059-0.095 | 20.9 | 35.3 |
| Fig.7 (a) | 0.064 | 30.0 | 19.9-15.3 | 0.051-0.081 | 21.3 | 35.1 |
| Fig.7 (b) | 0.065 | 29.9 | 15.4-20.0 | 0.050-0.080 | 21.2 | 35.0 |

## *Dynamic response at the beginning of a dehumidification process*

Experiments are conducted to study the dynamic characteristics at the beginning of a dehumidification process while the inlet conditions of the air and the desiccant solution are fixed. First, the air flows through the dehumidifier for a few minutes. As the packing is made of the porous material, a small amount of desiccant is stored in the interior of the packing due to the previous experiment tests. After the air is dehumidified and heated to the initial steady state, the desiccant solution enters the dehumidifier and the dehumidification experiment starts. The inlet conditions of the air and the desiccant solution remain unchanged during the entire test process. Table 3 shows the inlet conditions of this case.

Fig. 4 presents the test results showing the changing processes of both the air and the desiccant. For the air, it can be observed that both the humidity ratio and the temperature significantly drop and gradually reach the steady states. It spends nearly 180 seconds for the air humidity ratio achieving the steady state. While for the outlet air temperature, the time spend is about 220 seconds.

It also can be found that the humidity ratio and temperature of the outlet air are not equal to those of the inlet air during the initial 40 seconds when only the air flows into the dehumidifier (no solution enters). The reason is that the air is still dehumidified and heated by the desiccant stored in the packing although there is no desiccant solution entering the packing during this period, and it gradually reaches the initial steady state, as shown in Fig.4.

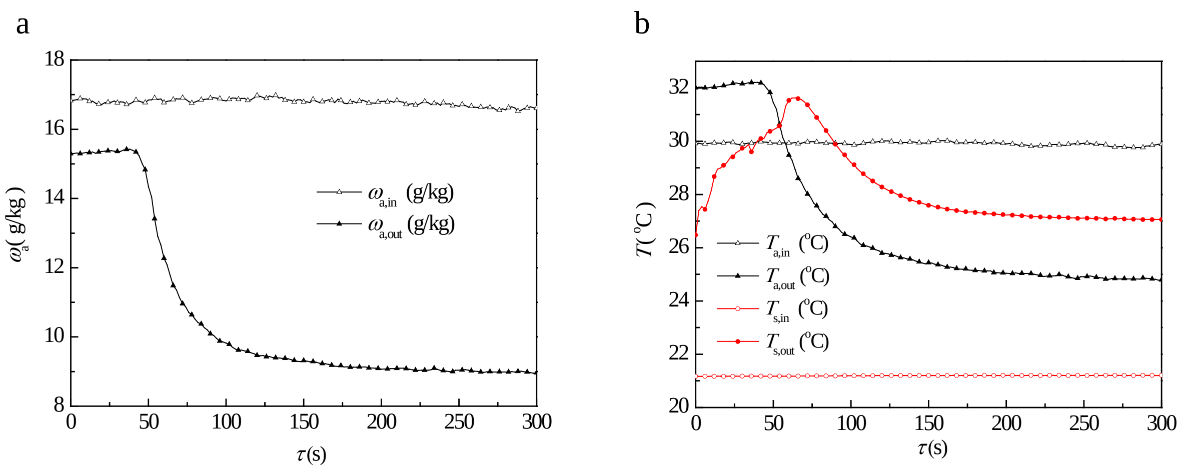


Fig. 4. Dynamics at the beginning of a dehumidification process: (a) inlet and outlet air humidity ratios and (b) inlet and outlet temperatures of air and solution.

It should be noted that the dynamic dehumidification process starts when the desiccant solution flows into the dehumidifier. The average velocity of the solution in the inclined packing channel is 0.05m/s, and it takes nearly 12 seconds for the desiccant solution flowing through the packing. The thermometer's reading of the outlet solution can not reflect the actual solution temperature during this period. The outlet solution temperature increases during this period because the thermometer is heated by the inlet air. The outlet solution temperature experiences a transient increase after the solution begins to flow out of the packing due to the heat transfer with the air and the latent heat by vapor condensation. It then decreases gradually to a steady state.

### *Dynamic response to the step changes of inlet parameters*

The step response method is a good way to study how a dynamic system responses to the drastic change of input parameters, it is introduced in this study to investigate the dynamic response of the dehumidifier. The inlet air humidity ratio and the solution flow rate are the two parameters which play important roles in the dehumidification process. Step change of either of the two parameters could result in significant disturbances that have immediate effects on the dynamic dehumidification process. In this section, dynamic responses of the dehumidifier to step changes of these two parameters are investigated, respectively. In addition, combined dynamic responses to simultaneous step changes of both of the two parameters are also investigated.

*Dynamic response to the step change of inlet air humidity ratio*

In this case, the dynamic responses of the outlet air and solution are studied when only the inlet air humidity ratio experiences step change (the other inlet conditions of the air and the solution are fixed). At the beginning of the test, the inlet air humidity ratio remains unchanged at 17.5g/kg. Then, three sequential step changes of the inlet air humidity ratio are made from 17.5g/kg to 13.8g/kg, 16.0g/kg, and 14.1g/kg, respectively, as shown in Fig.5.(a). Table 3 shows the inlet conditions of this case.

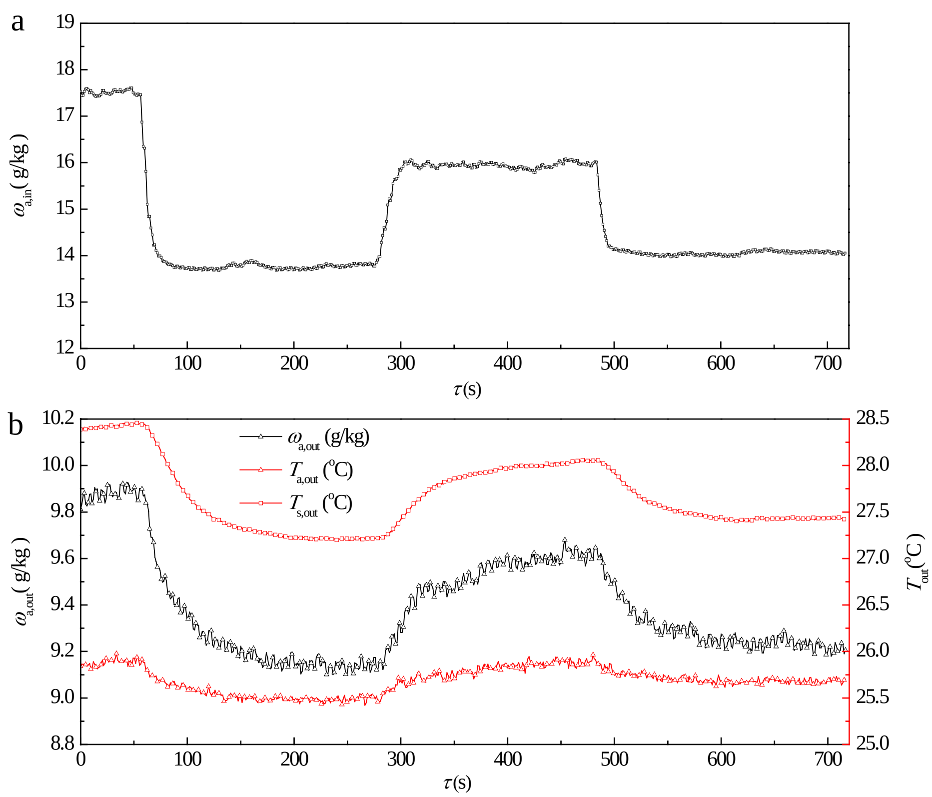


Fig. 5. (a) Step change of inlet air humidity ratio; (b) Dynamic response of outlet air and solution to the step change of inlet air humidity ratio.

The test results of the outlet air and solution are shown in Fig.5.(b). It can be found that the outlet air humidity ratio drops with the decrease of the inlet air humidity ratio, and rises with the increase of the inlet air humidity ratio. The outlet temperatures of the air and the solution experiences the same changing trends like the outlet air humidity ratio. However, the range of change of the outlet air temperature is much smaller than that of the outlet solution temperature. During each step response process, the measured outlet variables of the air and the solution basically achieve new steady states within 200 seconds, respectively. In the first step response process, the reason why both the outlet air and the outlet solution temperature decrease is that the condensation heat generated during the dehumidification process reduces when the inlet air humidity ratio decreases. The decrease of the outlet air and solution temperature in turn leads to a smaller outlet air humidity ratio.

*Dynamic response to the step change of solution flow rate*

Tests are also conducted to introduce three sequential step changes of the solution flow rate from 0.048kg/s to 0.098kg/s, 0.059kg/s and 0.095kg/s, respectively, which are shown in Fig.6.(a). The rest inlet conditions of this case remain constant, as shown in Table 3.

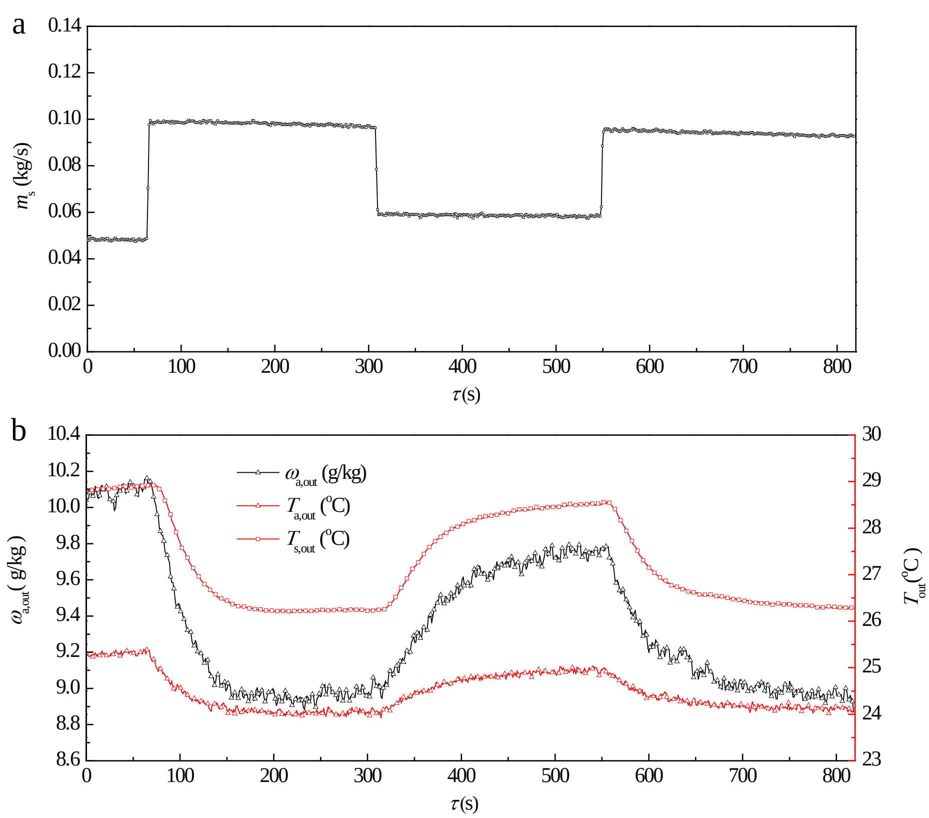


Fig. 6. (a) Step change of solution flow rate; (b) Dynamic response of outlet air and solution to the step change of solution flow rate.

Fig.6.(b) presents the measured results of the outlet air and solution. It can be observed that, during each

step response process (250s), all of the outlet variables of the air and the desiccant could achieve the new steady states. The results also illustrate that the outlet parameters ($\omega_{a,out}$, $T_{a,out}$, $T_{s,out}$) change in opposite to the solution flow rate. The reason is that, with the increase of the solution flow rate, the dehumidification capacity and the cooling capacity of the solution increase (the temperature of the inlet solution usually lower than that of the inlet air), which leads to the decrease of the outlet air humidity ratio and the outlet temperatures of the air and the solution.

*Dynamic response to simultaneous step changes of two inlet parameters*

In the above experiments, only one inlet parameter is changed in each test. In the practical applications, there is normally more than one inlet parameter that changes at the same time and affects the dehumidification process. It's beneficial to study the combined influence of multiple inlet parameters. Therefore, experiments are conducted through making step changes of both the inlet air humidity ratio and the solution flow rate simultaneously. Their combined influence on the dynamic responses of the outlet air are observed and analyzed. Two groups of experiments are conducted under the simultaneous step changes of two inlet parameters (i.e., the inlet air humidity ratio and the solution flow rate). In Group 1, the inlet air humidity ratio changes from 19.9g/kg to 15.3g/kg and the solution flow rate changes from 0.051kg/s to 0.081kg/s. In Group 2, the inlet air humidity ratio changes from 15.4g/kg to 20.0g/kg and the solution flow rate changes from 0.050kg/s to 0.080kg/s. The experimental inlet and outlet conditions of the air and the desiccant solution are shown in Table 3.

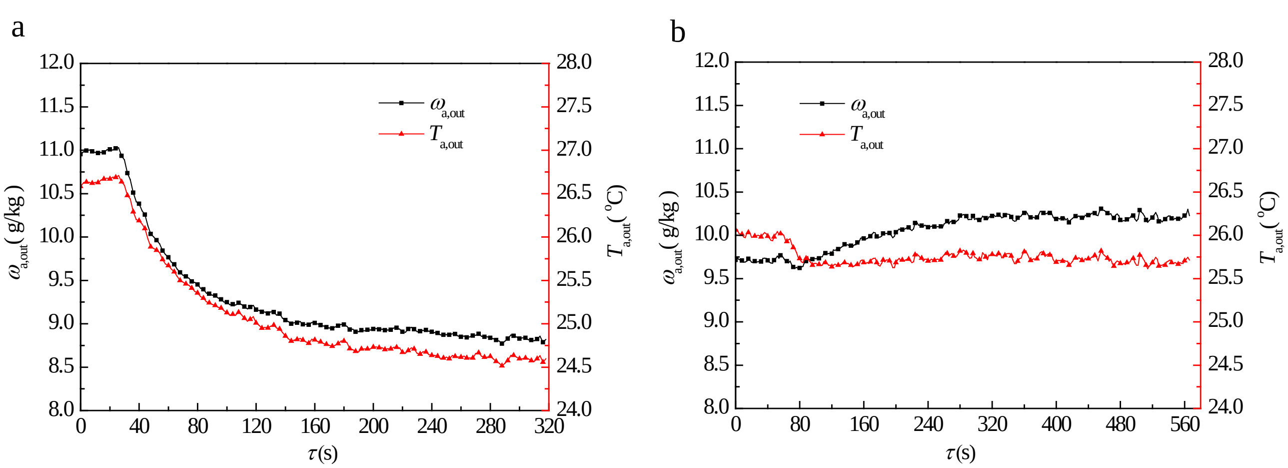


Fig. 7. Dynamic response of outlet air to simultaneous step changes of inlet air humidity ratio and solution flow rate: (a) similar effect, (b) contrary effect.

Fig.7 shows the dynamic response of the outlet air. According to the conclusion of previous sections, the increases of the inlet air humidity ratio and the solution flow rate have the contrary influences on the outlet air. The results in Fig.7.(a) indicate that, when the influences of different inlet parameters on the outlet air are similar (e.g., Group 1), their influences are superposed. However, the settling time of the outlet air has little change when compared with the single step change of inlet fluid parameter discussed in previous sections. When the influences of different inlet parameters are contrary (e.g., Group 2), their combined influences on the outlet air become complicated, which are shown in Fig.7.(b). The results indicate that it costs more time for the outlet air humidity ratio reaches the new steady state condition than that by a single step change of inlet fluid parameter. By contrast, the outlet air temperature becomes almost stable after a shorter time. It indicates that combined influence of different disturbance factors on the dynamic dehumidification processes is more complicated which needs further research.

## Parameter analysis of dynamic dehumidification processes

Parameter analysis is an effective approach to analyze the influence of various parameters on a process, which has been extensively applied in many research fields. The influence of one configuration parameter (i.e., the height of the packing) and two operation parameters (i.e., the air flow rate and the solution flow rate) on the dynamics of the dehumidifier are analyzed in this study. The influence of each parameter is investigated when the dehumidification process operates under different transient working conditions. The transient working conditions are established in two ways, i.e. testing at the beginning of a dehumidification process after a period of idle and introducing step changes to the inlet fluids parameters (i.e., air humidity ratio or solution flow rate) when the dehumidifier works stably. In different tests, different values are assigned to each parameters for identifying how the parameters influence the process.

In order to quantify and evaluate the dynamic characteristics of the dehumidifier, time constant of the dynamic response process is introduced. The time constant ($\tau_c$) is defined as the time when an outlet variable approaches 63.2% of the difference between the initial steady state and the final steady state (Namvar et al. 2012), which can be expressed as Eq.(8).

$$\boldsymbol{\Phi}(\boldsymbol{\tau}_{\mathbf{c}}) = \boldsymbol{\Phi}(\boldsymbol{i}) - \mathbf{0.632}(\boldsymbol{\Phi}(\boldsymbol{i}) - \boldsymbol{\Phi}(\boldsymbol{f})) \quad (8)$$

where $\boldsymbol{\Phi}$ represents either outlet air temperature or outlet air humidity ratio, $\tau_c$ represents time constant, $i$ represents initial steady state, $f$ represents final steady state. The time constant of the outlet air temperature represents the changing speed of heat transfer, while the time constant of the outlet air humidity ratio represents the changing speed of mass transfer.

The time constants of the outlet air are measured in each test and they are compared to evaluate the impacts of three parameters on the dynamic characteristics of the dehumidifier separately. In order to reduce the influences caused by measuring uncertainties, the measurements are arranged by fitted curves, and the time constants of the outlet air are determined from the fitting results.

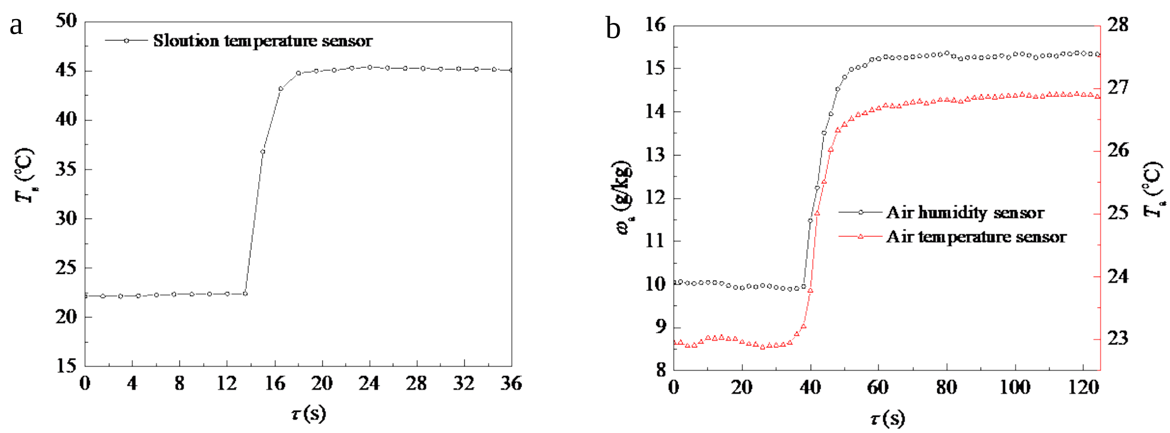


Fig. 8. Dynamic response of sensors to step changes: (a) solution temperature sensor to a step change in solution temperature, (b) air humidity and temperature sensors to simultaneous step changes in temperature and humidity testing.

The dynamic response of the sensors alone to a step change is also investigated, which is shown in Fig.8. The time constants are 1.5 seconds for the solution temperature sensor, 5 seconds for the air humidity sensor, 6 seconds for the air temperature sensor. The dynamic response of the air humidity sensor and temperature sensor is similar. It can be found that the response of the sensors is fast enough to be ignored when compared with dynamic response of the dehumidifier which discussed in the previous sections. The dynamic response of sensors can be included in the time constant of the dehumidifier (Namvar et al. 2012).

## *Tests at the beginning of a dehumidification process*

In this section, experiments are conducted to study the influences of two operation parameters (i.e., air flow rate, solution flow rate), and one configuration parameters (i.e., packing height) on the dynamic dehumidification process of the dehumidifier at the beginning of a dehumidification process. The beginning of a dehumidification process is of special interest because air conditioning systems in buildings seldom continuously operate 24 hours a day. The start-up of a dehumidifier after a period of idle is part of the start-up of the whole air conditioning systems, and is important to develop the operation strategies.

*Influence of air and desiccant solution flow rates*

Totally 9 groups of experiments are conducted on the dehumidifier with the packing height of 0.4m. Three levels of values are introduced to the two operation parameters (i.e. the air flow rate and the solution flow rate), respectively. Groups 1-3 represent the experiments under the conditions of the same high air flow rate with three different levels of solution flow rates, respectively. Similarly, Groups 4-6 represent the experiments under the same middle air flow rate and Groups 7-9 represent the experiments under the same low air flow rate. The experimental inlet and outlet conditions of the air and the desiccant solution are shown in Table 4. In Table 4, $\omega_{a,ini}$ and $T_{a,ini}$ are the humidity ratio and the temperature of the outlet air at the initial steady state before the desiccant solution flows into the dehumidifier. Time constants of the outlet air humidity ratio and temperature in each experiment are calculated according to Eq. (8), as shown in Table 4. The outlet solution concentration is not given in Table 4, which is nearly 0.2% less than its inlet condition in each test.

Table 4. Experimental inlet and outlet conditions of air and desiccant solution at the beginning of a dehumidification process with different air and solution flow rates.

| Group | $m_a$ (kg/s) | $T_{a,in}$ (°C) | $\omega_{a,in}$ (g/kg) | $m_s$ (kg/s) | $T_{s,in}$ (°C) | $X$ (%) | $\omega_{a,ini}$ (g/kg) | $T_{a,ini}$ (°C) | $\omega_{a,out}$ (g/kg) | $T_{a,out}$ (°C) | $T_{s,out}$ (°C) | $\tau_{c,\omega}$ (s) | $\tau_{c,T}$ (s) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.079 | 30.0 | 16.7 | 0.114 | 21.2 | 35.8 | 15.4 | 32.2 | 9.0 | 24.8 | 27.1 | 28 | 36 |
| 2 | 0.079 | 30.0 | 16.9 | 0.083 | 21.0 | 35.8 | 15.5 | 31.5 | 9.5 | 25.2 | 28.3 | 31 | 37 |
| 3 | 0.079 | 30.0 | 16.4 | 0.052 | 21.2 | 35.7 | 15.2 | 32.1 | 10.5 | 26.8 | 30.2 | 39 | 53 |
| 4 | 0.064 | 30.0 | 17.0 | 0.114 | 21.1 | 36.0 | 16.2 | 32.2 | 8.8 | 24.5 | 26.1 | 30 | 40 |
| 5 | 0.064 | 30.0 | 16.9 | 0.083 | 21.2 | 35.9 | 15.9 | 32.6 | 9.2 | 24.9 | 27.6 | 33 | 48 |
| 6 | 0.064 | 30.0 | 15.9 | 0.050 | 21.1 | 35.6 | 15.0 | 32.0 | 9.7 | 25.8 | 29.1 | 41 | 59 |
| 7 | 0.048 | 30.0 | 17.4 | 0.114 | 21.0 | 36.0 | 14.0 | 28.6 | 8.7 | 23.3 | 25.1 | 33 | 38 |
| 8 | 0.048 | 30.0 | 16.8 | 0.083 | 21.0 | 35.5 | 15.1 | 30.4 | 8.7 | 23.7 | 25.9 | 37 | 43 |
| 9 | 0.048 | 30.0 | 16.4 | 0.051 | 21.2 | 35.9 | 14.8 | 31.5 | 9.3 | 25.1 | 27.9 | 46 | 63 |

For the simplification, only the results of the variable solution flow rate tests are presented in the figures. The influence of the solution flow rate on the time constant of the outlet air is shown in Fig.9. The results show that the time constants of the outlet air humidity ratio are always smaller than that of the outlet air temperature, which indicate that the changes of mass transfer rate are faster than the changes of heat transfer rate in the unsteady state dehumidification processes. This finding is consistent with the experimental results of Namvar et al. (2012), although the time constants in their study are much larger. Fig.9 also indicates that the time constants of the outlet air decrease with the increase in the solution flow rate. However, the rate of decrease in the time constants becomes slower when the solution flow rate increases. It also can be found in Table 4 that the time constants of the outlet air also decrease generally with the increase in the air flow rate. The reason that the time constants of the outlet air decrease with the increase in the solution flow rate or the air flow rate could be that higher solution or air flow rate can enhance the heat and mass transfer rates and more latent heat can be taken away by the fluid.

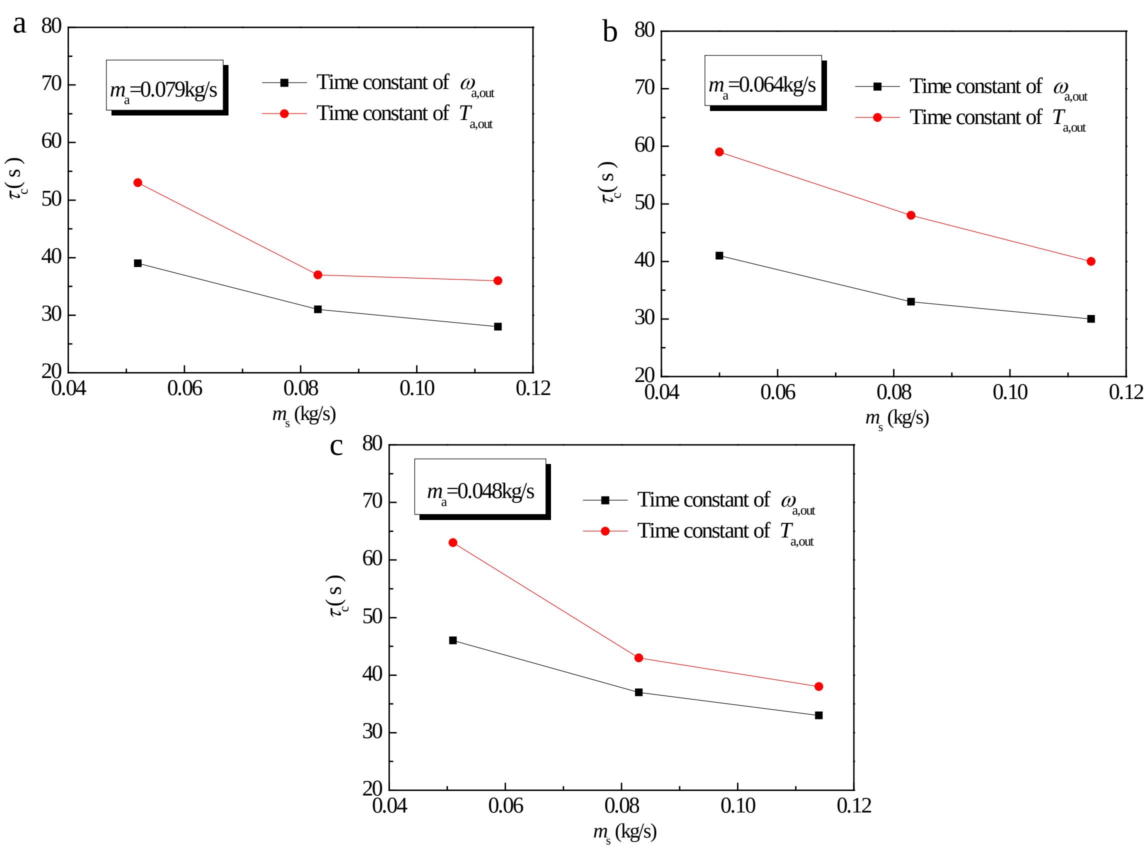


Fig. 9. The influence of solution flow rate on time constants of outlet air when (a) $m_a$=0.079kg/s, (b) $m_a$=0.064kg/s, (c) $m_a$=0.048kg/s.

As an example, Fig.10 presents the measured dynamic response of the outlet air under three different solution flow rates when the air flow rate is 0.079kg/s.

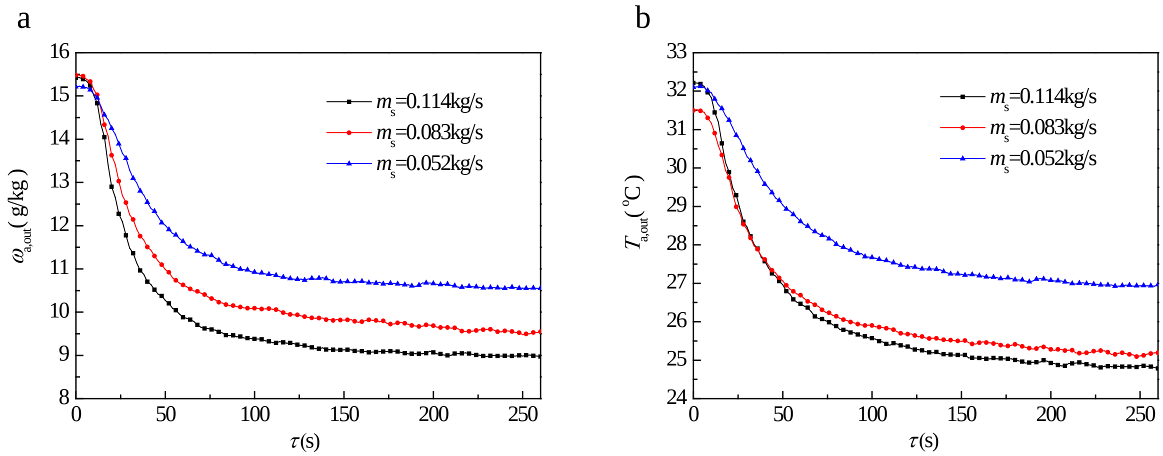


Fig. 10. Dynamic response of outlet air at different solution flow rates: (a) outlet air humidity ratio, (b) outlet air temperature. ($m_a$=0.079kg/s)

*Influence of packing height*

The influence of the packing height on the dynamic response of the outlet air at the beginning of a dehumidification process is investigated with fixed inlet fluids conditions. Three packing heights (i.e., 0.3m, 0.4m and 0.5m) are employed under the same inlet conditions. The inlet and outlet conditions are presented in Table 5.

Table 5. Experimental inlet and outlet conditions of air and desiccant solution at the beginning of a dehumidification process with different packing heights.

| $H$ (m) | $m_a$ (kg/s) | $T_{a,in}$ (°C) | $\omega_{a,in}$ (g/kg) | $m_s$ (kg/s) | $T_{s,in}$ (°C) | $X$ (%) | $\omega_{a,ini}$ (g/kg) | $T_{a,ini}$ (°C) | $\omega_{a,out}$ (g/kg) | $T_{a,out}$ (°C) | $T_{s,out}$ (°C) | $\tau_{c,\omega}$ (s) | $\tau_{c,T}$ (s) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.3 | 0.079 | 29.9 | 17.2 | 0.083 | 21.3 | 35.7 | 16.0 | 32.0 | 10.3 | 26.3 | 28.4 | 30 | 36 |
| 0.4 | 0.079 | 30.0 | 16.9 | 0.083 | 21.0 | 35.8 | 15.5 | 31.5 | 9.5 | 25.2 | 28.3 | 31 | 37 |
| 0.5 | 0.078 | 29.9 | 16.9 | 0.083 | 21.2 | 35.6 | 16.1 | 33.3 | 9.3 | 25.5 | 28.7 | 35 | 51 |

The dynamic responses of the outlet air are shown in Fig.11. It can be observed that the time constants of both the outlet air humidity ratio and the outlet air temperature increase with the packing height. The time constants change faster with a higher height. The results in Fig.11 also show that the time constants of the outlet air temperature are larger than that of the outlet air humidity ratio under various packing heights.

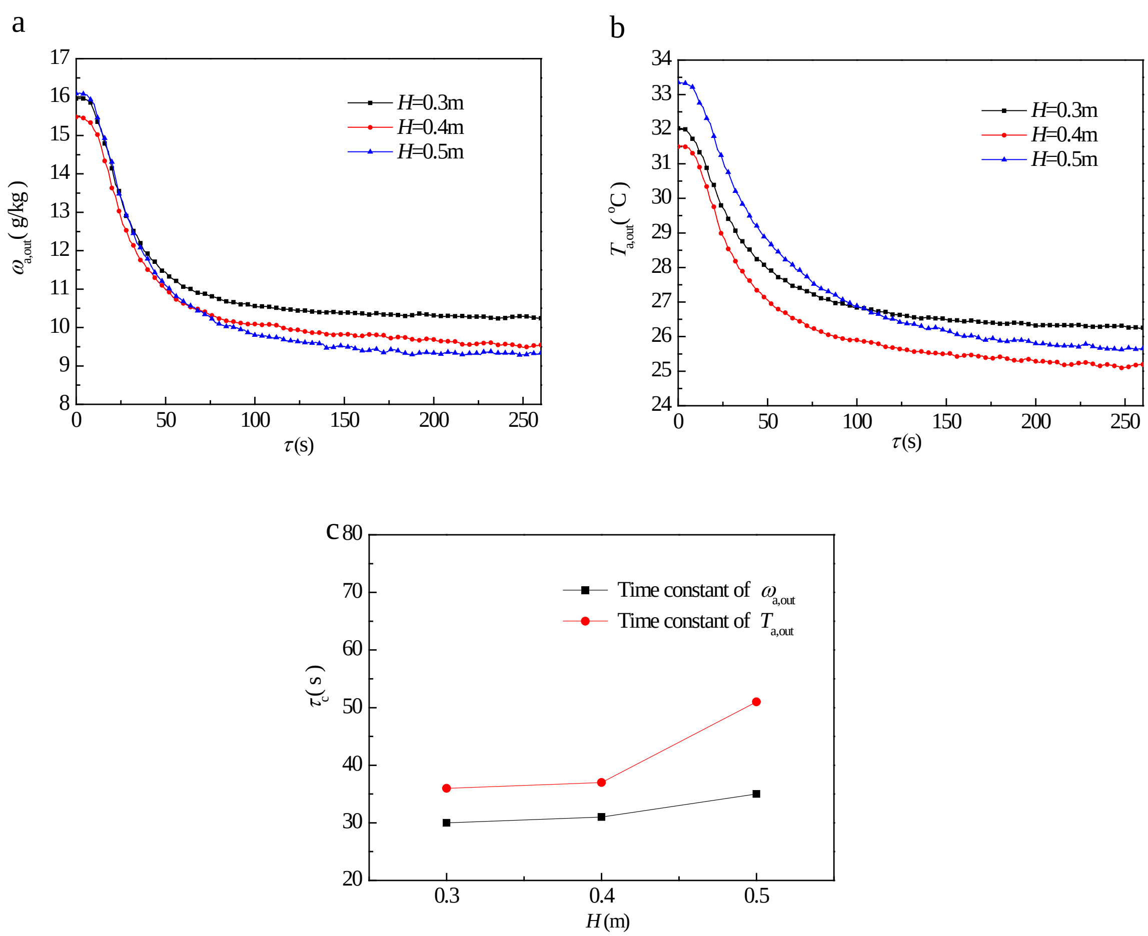


Fig. 11. Dynamic response of outlet air at the beginning of a dehumidification process with different packing heights: (a) outlet air humidity ratio, (b) outlet air temperature, (c) time constants of outlet air temperature and humidity.

## *Tests under step changes of inlet fluids parameters*

In this section, experiments are conducted to investigate the impacts of three parameters (i.e., air flow rate, solution flow rate and packing height) on the dynamic dehumidification process of the dehumidifier under the transient working conditions with the step changes of inlet fluids parameters (i.e., air humidity ratio or solution flow rate). Step changes of the inlet air humidity ratio are introduced into the tests of the influence of the air flow rate and the solution flow rate. Step changes of the inlet solution flow rate are introduced into the tests of the influence of the packing height.

*Influence of air and desiccant solution flow rates*

Table 6. Experimental inlet and outlet conditions of air and desiccant solution with different air and solution flow rates. *(Step changes are introduced to the inlet air humidity ratio)*

| Group | $m_a$ (kg/s) | $T_{a,in}$ (ºC) | $\omega_{a,in}$ (g/kg) | $m_s$ (kg/s) | $T_{s,in}$ (ºC) | $X$ (%) | $\omega_{a,out}$ (g/kg) | $T_{a,out}$ (ºC) | $T_{s,out}$ (ºC) | $\tau_{c,\omega}$ (s) | $\tau_{c,T}$ (s) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.079 | 30.0 | 17.0-12.3 | 0.082 | 21.3 | 35.8 | 9.7-8.4 | 25.5-24.5 | 28.5-26.3 | 31 | 42 |
| 2 | 0.063 | 30.0 | 17.0-12.4 | 0.080 | 21.2 | 35.6 | 9.1-8.1 | 24.5-23.7 | 27.5-25.5 | 32 | 46 |
| 3 | 0.049 | 30.0 | 17.2-12.8 | 0.082 | 21.2 | 35.8 | 8.6-7.7 | 24.0-23.3 | 26.3-24.8 | 39 | 53 |
| 4 | 0.063 | 30.0 | 17.0-12.3 | 0.113 | 21.3 | 35.7 | 8.7-7.7 | 23.9-23.3 | 26.1-24.6 | 30 | 31 |
| 5 | 0.063 | 30.0 | 17.0-12.4 | 0.080 | 21.2 | 35.6 | 9.1-8.1 | 24.5-23.7 | 27.5-25.5 | 32 | 43 |
| 6 | 0.064 | 30.0 | 17.2-12.3 | 0.049 | 21.1 | 35.5 | 10.1-8.6 | 25.5-24.4 | 29.9-27.0 | 55 | 64 |

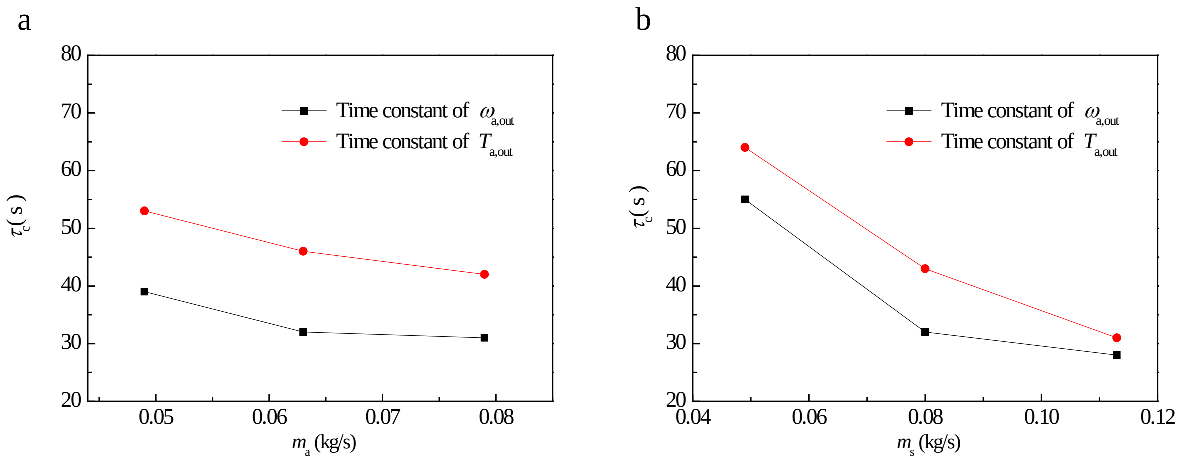


Fig. 12. (a) The influence of air flow rate on time constants of outlet air, (b) The influence of solution flow rate on time constants of outlet air.

The influence of the air flow rate and the solution flow rate are studied separately under the transient working conditions with the step changes of inlet fluids parameters. The air flow rate and the solution flow rate are assigned three values respectively for 6 groups of experiments. In each group of test, the transient working conditions is established by making step change of the inlet air humidity ratio from a high value (17.0-17.2g/kg) to a lower value (12.3-12.8g/kg). The outlet air temperature and humidity ratio are observed when the inlet air flow rate and the inlet solution flow rate are set at different values, separately. Table 6 lists the measured inlet and outlet conditions of the air and the desiccant solution. Groups 1-3 represent the experiments under three different air flow rates (the solution flow rate is fixed). Groups 4-6 represent the experiments at three different solution flow rates (the air flow rate is fixed).

Fig.12 shows the time constants of the outlet air humidity ratio and the outlet air temperature obtained in the tests. It can be found that the time constants of the outlet air decrease with the increase of the flow rates of both air and solution. The rate of decrease becomes smaller with increasing flow rates. The above test results are similar to those in the analysis of the beginning of a dehumidification process.

As an example, the dynamic characteristics of the outlet air in response to the step changes of the inlet air humidity ratio at different air flow rates are shown in Fig.13. The results in Fig.13 show the outlet air experiences a dynamic process from one steady state to a new steady state within 200 seconds.

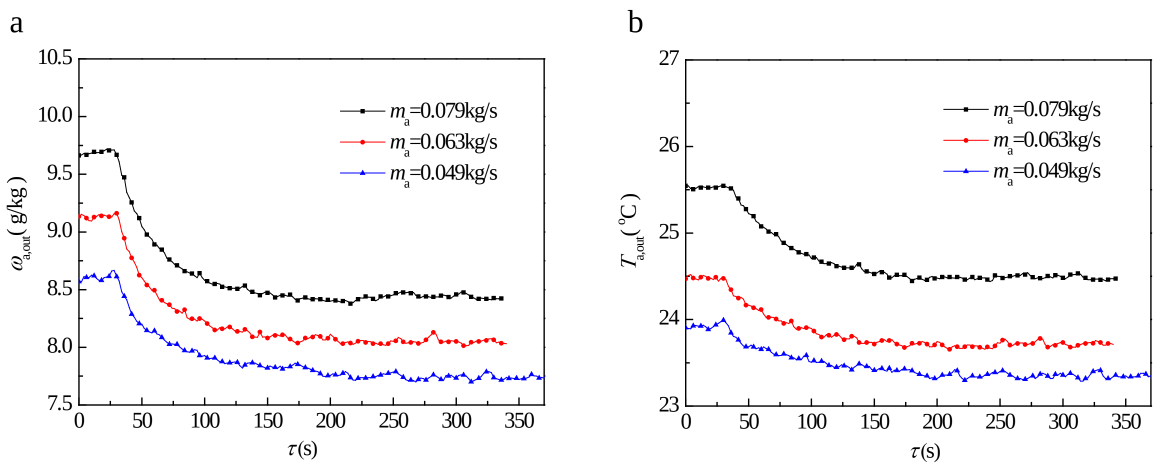


Fig. 13. Dynamic response of outlet air at different air flow rates: (a) outlet air humidity ratio, (b) outlet air temperature.

*Influence of packing height*

Three experiments with different packing heights are conducted to study the influence of the packing height under the transient working conditions with the step change of the inlet solution flow rate. Three packing heights (i.e. 0.3, 0.4 and 0.5m) are introduced into the three experiments. For each experiment, transient working condition is created by introducing the step change of the solution flow rate from 0.05kg/s to 0.08kg/s. Table 7 shows the detailed inlet and outlet conditions as well as the packing heights used in the experiments.

The dynamic responses of the outlet air are shown in Fig.14. It can be observed that the relationship between the packing height and the time constants of the outlet air is similar to the results in the analysis of the beginning of a dehumidification process. The major difference is the changing rate of the time constants in this case decreases with the increase of the packing height.

Table 7. Experimental inlet and outlet conditions of air and desiccant solution with different packing heights. *(Step changes are introduced to the solution flow rate.)*

| $H$ (m) | $m_a$ (kg/s) | $T_{a,in}$ (°C) | $\omega_{a,in}$ (g/kg) | $m_s$ (kg/s) | $T_{s,in}$ (°C) | $X$ (%) | $\omega_{a,out}$ (g/kg) | $T_{a,out}$ (°C) | $T_{s,out}$ (°C) | $\tau_{c,\omega}$ (s) | $\tau_{c,T}$ (s) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.3 | 0.079 | 29.9 | 16.7 | 0.051-0.082 | 21.3 | 35.5 | 10.8-9.9 | 27.0-25.9 | 29.9-28.2 | 31 | 34 |
| 0.4 | 0.079 | 30.0 | 17.1 | 0.052-0.083 | 21.3 | 35.7 | 10.7-9.7 | 27.0-25.5 | 30.8-28.5 | 42 | 50 |
| 0.5 | 0.078 | 29.9 | 16.8 | 0.051-0.080 | 21.2 | 35.5 | 10.3-9.2 | 26.6-25.1 | 30.8-28.8 | 44 | 55 |

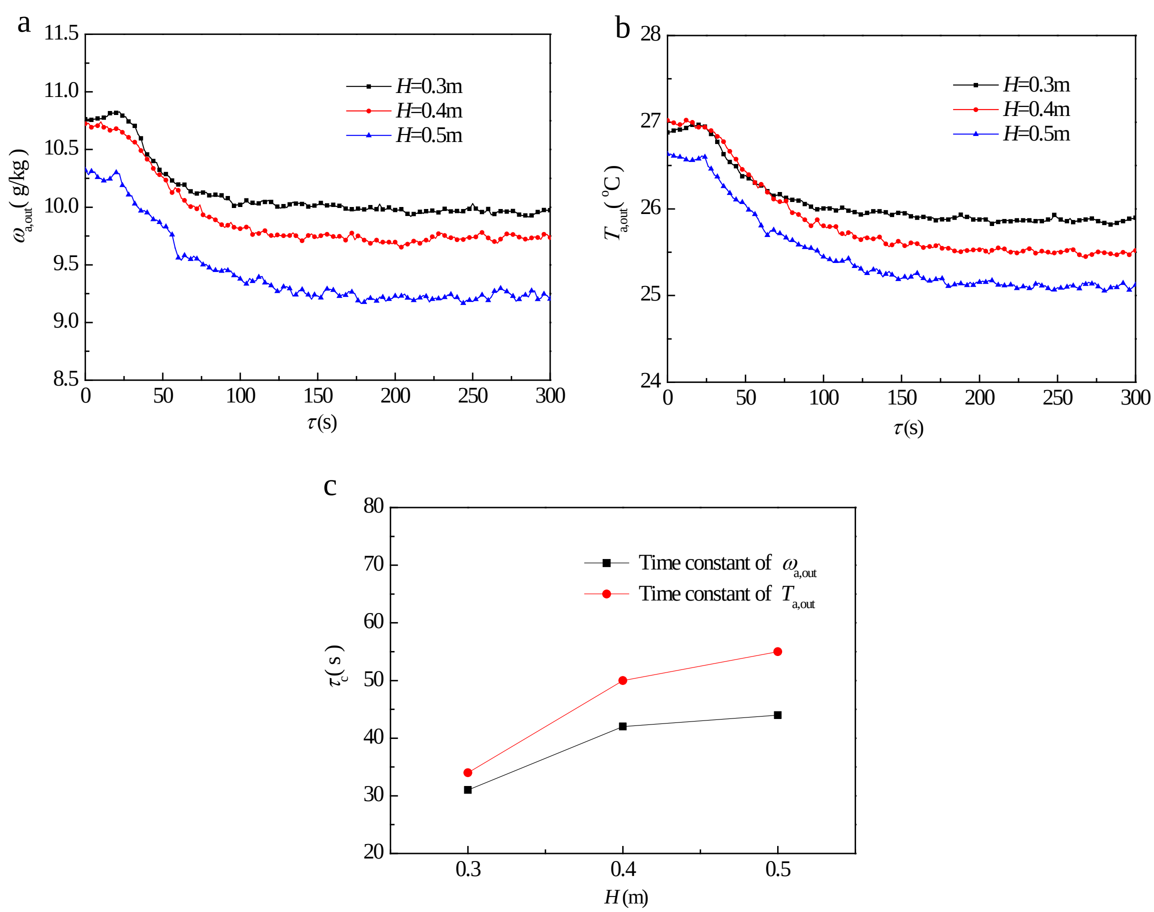


Fig. 14. Dynamic response of the dehumidifier with different packing heights: (a) outlet air humidity ratio, (b) outlet air temperature, (c) time constants of outlet air temperature and humidity.

## Conclusion

An experimental platform involving the packed-type liquid desiccant dehumidifier is established to study the dynamic heat and mass transfer characteristics of the dehumidifier. Two types of transient working conditions are generated by experiments: at the beginning of a dehumidification process with the fixed inlet fluids parameters and the step changes of inlet fluids parameters (i.e., air humidity ratio or the solution flow rate). First, the general dynamic characteristics of the dehumidification process under the two types of transient working conditions are investigated. The test results illustrate that the outlet air and desiccant solution normally vary in the form of exponential curves for each dehumidification process. For at the beginning of a dehumidification process with the fixed inlet fluids conditions, it needs nearly 180 seconds for the air humidity ratio or about 220 seconds for the outlet air temperature achieving the steady state. For the step change conditions, the transient time of the outlet air and solution to reach the new steady states is about 200 seconds in the tests of this study. The step response analysis also indicate that the influences of the inlet air humidity ratio and the solution flow rate on the outlet conditions are opposite. In addition, a response analysis to simultaneous step changes of two inlet parameters is conducted to study their combined effects on the dynamic characteristics of the dehumidification processes. The results indicate that, when the effects of the two inlet parameters on the outlet air are similar, their effects are superposed and become greater. While the time for the outlet air achieving the steady state has no obvious change. When the effects are contrary, more time is needed for the outlet air humidity ratio to reach a new stable state. But the outlet air temperature achieves stable in a shorter time.

The influences of the air flow rate, the solution flow rate and the packing height on the dynamics are further studied by experiments using the parameter analysis method. Time constants of the dehumidification process concerning the outlet air temperature and humidity ratio are obtained. The time constants of the outlet air temperature (around 35s to 60s) are larger than that of the humidity ratio (around 30s to 50s) in all tests. The results indicate that the time constant decreases when the air flow rate or the solution flow rate increases for a given dehumidifier. The rate of decrease becomes slower at a higher air and solution flow rate. The time constants are not significant because of the small scale and small thermal capacity of the dehumidifier. The results also show that the packing height obviously influences the dynamic dehumidification process. The time constant of the outlet air temperature increases from 34s to 55s when the packing height increases from 0.3m to 0.5m. More detailed theoretical analysis of the time constant based on dynamic modeling will be the focus of the following work.

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## Nomenclature

| | |
|---|---|
| $h$ | specific enthalpy (kJ/kg) |
| $H$ | height of packing (m) |
| $m$ | mass flow rate (kg/s) |
| $m_{de}$ | moisture removal rate of air (g/s) |
| $MD$ | mean deviation (-) |
| $N$ | the number of experiment under steady state (-) |
| $Q$ | enthalpy variation (kW) |
| $T$ | temperature (ºC) |
| $X$ | mass concentration of solution (%) |

*Greek symbols*

| | |
|---|---|
| $\tau$ | time (s) |
| $\tau_c$ | time constant of outlet air (s) |
| $\omega$ | humidity ratio (g/kg) |

*Subscripts*

| | |
|---|---|
| a | air |
| in | inlet |
| ini | initial steady state |
| out | outlet |
| s | solution |
| T | temperature |
| ω | humidity ratio |

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