Modeling and control of dehumidifier in distributed operating liquid desiccant dehumidification system

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**MODELING AND CONTROL OF DEHUMIDIFIER
IN DISTRIBUTED OPERATING LIQUID
DESICCANT DEHUMIDIFICATION SYSTEM**

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ENERGY RESEARCH INSTITUTE @ NTU (ERI@N)**

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A thesis submitted to the Nanyang Technological
University in partial fulfilment of the requirement for
the degree of
Doctor of Philosophy

2017

Statement of Originality

I hereby certify that the work embodied in this thesis is the result of original research and has not been submitted for a higher degree to any other University or Institution.

..... 13 July 2017
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Abstract

Liquid Desiccant Dehumidification System (LDDS) achieves low humidity level with relatively low energy consumption, which is an outstanding alternative to conventional air-conditioning system in removing the moisture in the air. In industrial or commercial buildings, dehumidifiers of LDDS are usually located at different floors in a distributed manner, while the heat source utilized for regeneration such as the waste heat or solar energy are in the plant room or on the rooftop in a centralized form. Conventional LDDSs regulate the solution concentration in the dehumidifier by continuously exchanging the desiccant solution between dehumidifier and regenerator, which limits LDDS to a one dehumidifier vs. one regenerator arrangement. To take full advantage of the building recourses, a scheme of multiple dehumidifiers working with one regenerator is more efficient. Meanwhile, new technical issues have been raised together with this mechanism, such as detecting and maintaining solution concentration and the solution transfer among the components of a system with multiple terminals. Therefore, this thesis tries to provide some deep discussions on the questions generated from the distributed operating manner to further popularize LDDS in building application.

The major contributions are as follows:

A buffer integrated dehumidifier has been proposed to realize the distributed operation, and new mathematical model has been developed and validated to describe the dynamic profiles of the dehumidification and concentration variation process during the system operating, including the moisture absorption, strong solution charging, solution mixing, circulating and excavating.

A concentration regulation strategy has been developed to control the working solution concentration in the dehumidifier. Model-based soft-sensors are designed to detect the working solution concentrations of dehumidifier and regenerator to provide the concentration information of the two towers for the regulation strategy. Experimental studies on an actual system have been carried out to further verify the efficiency of this concentration regulation strategy with the assistance of the soft-sensors.

By considering the relations between working solution concentration and

energy consumptions, Genetic Algorithm (GA) is employed to obtain the optimal combination of weak and strong desiccant concentrations, solution and chilled water mass flow rates in dehumidification side for energy-saving purpose. Component and overall energy consumptions have been discussed and compared to analyze the energy performance at different working conditions to justify the distinctions of the GA selected input pairs among those applicable input combinations.

The working solution concentrations in dehumidifier and regenerator are measured and regulated to the optimal combination generated from the GA optimizer, and the fuzzy-PID controller tunes the outlet air humidity by regulating the inlet solution temperature. The indices IAE, ITAE and ISE are utilized to evaluate the performances of these combined modules. With some simplifications, these strategies are applied on a test rig following the distributed operating strategy to validate the feasibility of the proposed method.

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Abbreviations

Letters

A	heat transfer area (m^2)
D	tube diameter (m)
E	Energy(kJ)
ΔH	vaporization/condensation heat (kJ/kg)
$\dot{H}_s$	heat transfer rate (kw)
HR	function of humidity ratio (g/kg dry air)
K'_G	mass transfer coefficient ($\text{kg}/(\text{m}^3 \cdot \text{s} \cdot \text{pa})$)
M	mass (kg)
NTU	number of transfer units
RH	relative humidity (g/kg dry air)
S	cross area of dehumidification column (m^2)
T	temperature ($^{\circ}\text{C}$)
V	volume (m^3)
$\dot{V}$	volume flow rate (m^3/s)
a	parameters of energy models
c	concentration of desiccant solution
$\hat{c}_1 - \hat{c}_9$	parameters of heat and mass transfer model
c_p	specific heat (kJ/kg $^{\circ}\text{C}$)
$\tilde{c}_p$	dynamic specific heat (kJ/kg $^{\circ}\text{C}$)
d	humidity ratio of the air (g/kg dry air)
h'	heat transfer coefficient ($\text{w}/(\text{m}^2 \cdot ^{\circ}\text{C})$)
h_1	height of liquid in the strong solution buffer (m)
h_2	vertical height of the connecting tube between the two tanks (m)
L	tube length (m)
$\dot{m}$	mass flow rate (kg/s)
N_{H_2O}	mass transfer rate of H_2O ($\text{kg}/\text{m}^3 \cdot \text{s}$)
p_a	water vapor pressure of air (kpa)
p_s^*	water surface vapor pressure of desiccant solution (kpa)
t	time duration (s)
v	velocity of strong solution (m/s)

Creek letters

α	effective mass transfer area (m^2/m^3)
β	energy distribution ratio
η	energy efficiency
ε	void fraction of packing
ζ	coefficient of local resistance
λ	friction coefficient
μ	dynamic viscosity of the fluid ($\text{pa}\cdot\text{s}$)
ρ	density of desiccant solution (kg/m^3)
$\tilde{\rho}$	dynamic density (kg/m^3)

Subscripts

<i>a</i>	process air
<i>cw</i>	chilled water
<i>cssus</i>	energy consumed for the operation cooling source
<i>D</i>	dehumidifier
<i>dilu</i>	diluted desiccant solution
<i>f</i>	fan
<i>Hex</i>	heat exchanger
<i>hssus</i>	energy consumed for the operation heat source
<i>in</i>	the inlet of components or pipes
<i>lower</i>	lower range
<i>lowG</i>	low grade heat
<i>mix</i>	fully mixed desiccant solution
<i>mid</i>	median value
<i>nom</i>	nominal value
<i>out</i>	the outlet of components or pipes
<i>R</i>	regenerator
<i>p</i>	pump
<i>s</i>	desiccant solution
<i>stcs</i>	energy consumed by cooling source
<i>sths</i>	energy consumed by heat source
<i>str</i>	strong desiccant solution
<i>sp</i>	set point

trf solution transfer

upper upper range

w water

Chapter 1. Introduction

1.1 Background

Recent decades, energy crisis becomes a worldwide issue. Among the total energy consumption all over the world, a significant portion is consumed by buildings, and much of the building consumed energy is for air-conditioning systems. Especially in tropical countries like Singapore, air-conditioning systems consume 52% of the energy consumed in commercial buildings and 30% in residential buildings [1]. Energy efficiency of air-conditioning system is a challenging topic, and many new attempts have been made by engineers and scientists to improve the conventional system. The major task of air-conditioning system is providing treated air to the supply rooms, and one of the criterions to evaluate its performance is Indoor Environment Quality (IEQ). Humidity is one of the controllable parameters of IEQ which is important in terms of human comfort and health. Removing the excessive air moisture is more complex than maintaining the target temperature, which emphasizes the importance of air dehumidification.

Commonly utilized strategies to remove the moisture from the air are cooling-based dehumidification, solid desiccant dehumidification and liquid desiccant dehumidification. Cooling-based dehumidification is widely utilized in building systems. Air passes through evaporator coils and gets cooled, and the moisture condenses when the air temperature drops below the dew point. Then, the dry air is reheated and supplied to the room. Though simple, this method has drawbacks. Cooling-based dehumidification is less efficient in cold climates, while overcooling and reheating wastes energy [2]. Coolers typically work in a moist environment and need to be cleaned regularly to avoid the growth of mold to guarantee the quality of the supplied air.

Two types of widely utilized solid desiccant dehumidifiers are the solid packed tower and the rotating beds. In the packed tower dehumidifier, the process air flows through the tower of solid desiccant, and its moisture is transferred to the dry desiccant. When the solid desiccant is saturated with moisture, the air will be diverted to another drying tower, while the first tower is heated with reactivated air to regenerate the dehumidification ability [3]. Rotary desiccant wheels replace the towers with a rotary system, which is

operated by continuously rotating between two airstreams. One section of the wheel is in contact with the humid air stream, where moisture is adsorbed by the solid desiccant, and the other section contacts with the hot air and removes those absorbed moisture [4]. The solid desiccant requires high regeneration temperatures that restrict the possible choice of heat sources. Besides, the process air and reactivated air pass through the same desiccant wheel during the operation alternately, and eventually degrades the quality of supplied air.

A new type of air-conditioning system operating with triethylene glycol was designed by Lof in 1955 [5]. The development of LDDS goes very fast afterwards. Many improvements on liquid desiccants, system structures and optimization strategies have been made recently. Generally, LDDS consists of a dehumidifier and a regenerator. The dehumidifier absorbs the air moisture owing to the direct contact between the liquid desiccant and process air, and provides cool and dry air to the room. The regenerator concentrates the diluted solution to acceptable levels and transfers the solution back to the dehumidifier [6]. Compared with other dehumidification approaches, LDDS has the potential to apply low-grade heat and renewable energy sources [7-12], to prevent the growth of bacteria [13, 14], to avoid unnecessary water condensation, and to control the air humidity [15, 16]. Numerous efforts have been devoted to implementing LDDS in industrial or commercial buildings to handle the latent loads [17-19] recent years due to the merits mentioned above.

1.2 Motivations and objectives of the thesis

Multiple dehumidifiers need to be arranged on different floors to deal with the latent heat of the various zones to use LDDS in buildings at large scales. Furthermore, to conserve energy, low-grade heat should be considered as the driving force of regeneration. Some technical difficulties prevent the broad application of distributed LDDS, and the issues that need to be investigated and resolved are listed below.

- **The structure of dehumidifier for distributed operation.**

The major obstacle of promoting the application of distributed LDDS is that different dehumidification terminals require different desiccant concentrations. Moreover, the concentration of the working solution in the dehumidifier gradually decreases as the desiccant solution absorbs air

moisture. The energy consumption during the solution transfer accumulates, especially when the components are at specific distances in real buildings. A new operational method is required to overcome these problems and generalize the distributed operating strategy.

- **A dehumidifier model emphasizing the concentration profile is needed.**

Most of the dehumidifier models focus on steady-state heat and mass transfer. Though some efforts have been made to address the dynamic performance, these proposed models are not sufficient in describing the concentration profile of the buffer-integrated dehumidifier. Therefore, the existing models are not fit to investigate the system performance in distributed operations, and a new dynamic model is required to further discuss this newly proposed operation manner.

- **The regulation of the concentration of the working solution in dehumidifiers.**

Each dehumidifier has a discrete working solution concentration depending on the operating environment. When multiple terminals exist in the same system, a reasonable scheduling of concentrations in the dehumidifiers and regenerator is indispensable. The solution concentration inside the dehumidifiers and regenerator should be measured accurately to maintain the working solution concentration at the required level.

- **The optimal working solution concentrations.**

The optimal operating concentrations need to be selected among the feasible choices for the purpose of energy conservation. The energy usage of different components, such as dehumidifiers, cooling and heating sources, is considered to choose the best working solution concentrations of the components in a distributed operation.

- **Strategy to control the air humidity.**

Humidity is a critically important parameter to be controlled for better IEQ. Because the dehumidification performance of an LDDS is evaluated by the outlet air humidity, a control strategy is needed for all dehumidification terminals in a distributed LDDS to maintain the required moisture amount in the supply air.

The objective of this thesis is to solve the technical issues in a distributed operating LDDS and satisfy the requirements of the large-scale application of LDDS in real buildings. The specific topics discussed in this thesis are listed below.

- Improve the current LDDS structure for distributed applications;
- Develop an accurate dynamic model that involves concentration profiles;
- Propose and validate a strategy to maintain the working solution concentration of the dehumidifier;
- Determine the optimal working solution concentration pairs for dehumidifier and regenerator for saving energy;
- Provide a control strategy to regulate the humidity of the supplied air.

1.3 Major contributions

The major contributions of this thesis are listed accordingly:

- **Propose a distributed operating LDDS for building application.**
A multiple-dehumidifier vs. one-regenerator mode is introduced to improve the applicability of LDDS in building systems. Different dehumidifiers work independently to provide treated air to various zones, and the regenerator regenerates the desiccant solution at a central point. The available building resources such as the renewable heat, waste heat and piping system can be used to benefit the distributed LDDS operating with the proposed working strategy.
- **Dynamic model of the buffer-integrated dehumidifier.**
A dynamic model of a buffer-integrated dehumidifier has been developed. Compared with conventional dynamic models that regard the concentration as an uncontrollable variable, the proposed model manipulates the working solution concentration to describe the concentration profiles during the system operation. Simulations and experiments have been carried out to validate the efficiency of the proposed model.
- **Regulation of the working solution concentration based on soft sensors.**

The concentration regulation method applied to the proposed dehumidifier has been well investigated. Based on the mass balance of water, the working solution concentration in the dehumidifier is manipulated to avoid

the continuous solution swapping between dehumidifier and regenerator. Consequently, allows multiple dehumidifiers to work simultaneously with one regenerator. Simulations and experiments are conducted to validate this concentration regulation strategy. Model-based soft-sensors are utilized to detect the working solution concentration of dehumidifier and regenerator for concentration regulations.

- **Select the energy optimal working solution concentration pairs**

Many combinations of strong and weak solution concentrations can achieve the same dehumidification effect, whereas working with different concentrations leads to different energy consumptions. The Genetic Algorithm is employed to select the optimal working solution concentration pairs for energy conservation. The energy-saving performances at various concentrations and operating conditions are compared to confirm the importance of selecting the appropriate working solution concentration.

- **Design a fuzzy-PID controller to tune the outlet air humidity ratio.**

A fuzzy-PID controller has been developed to fine tune the outlet air humidity. The performance of this controller is validated together with the previously introduced modules. Simulations and experiments are carried out and indices, such as IAE, ITAE, and ISE, are used to evaluate the feasibility of the proposed strategy comprehensively.

1.4 Organization of the thesis

The rest of this thesis is organized as follows:

Chapter 2 surveys the literature on the design, control, and optimization of LDDS. With a clear knowledge of the existed findings, the key challenges and contributions relating to this thesis are addressed more clearly.

Chapter 3 covers the working principles of the distributed LDDS and descriptions of the experimental platform. All the experimental validations stated in this thesis have been conducted on the platform explained in this chapter. A mathematical model is introduced to describe the desiccant concentration profiles during operation, including the mixing and transfer of the desiccant solution.

Chapter 4 provides the approach of measuring and maintaining the working

solution concentration in the dehumidifier. The working solution concentrations in the dehumidifier and regenerator are measured by model-based soft sensors. Simulations and experiments are conducted to evaluate the performance of this concentration regulation strategy with various disturbances.

Chapter 5 introduces the strategy to select the optimal pairs of strong and weak desiccant solutions among the suitable combinations for energy conservation. The experimentally verified models are used to describe the physical relations and energy consumptions of individual components, including the dehumidifier, regenerator, cooling and heating sources, and transfer processes. Genetic Algorithm is employed to calculate the optimal working solution concentration pairs within the design and operating constraints.

Chapter 6 clarifies the effectiveness of humidity control with all the modules explained in this thesis. A fuzzy-PID controller is proposed to fine tune the outlet air humidity, and the working solution concentration in the dehumidifier is regulated according to the strategy in Chapter 4 to maintain the concentration at the optimal set point from Chapter 5. Simulations and experiments are conducted to validate the proposed strategy thoroughly.

Chapter 7 concludes the contents of this thesis and summarizes some potential future works as well.

Chapter 2. Literature Review

2.1 Introduction

Though numerous efforts have been devoted to implement LDDS in industrial or commercial buildings, as a new alternative to conventional cooling-based dehumidification, LDDS is still a new technology needs further investigations. To explicate the current research situations of LDDS and strengthen the contributions of this thesis, this chapter presents a comprehensive survey of LDDS on four aspects: properties of liquid desiccants, improvement of LDDS structure, modeling and analysis of dehumidifiers and control performances of the system.

2.2 Properties of liquid desiccants

Liquid desiccants have a high affinity of water vapor and this hygroscopic property makes them practical to absorb the moisture in the process air. From physical and thermal dynamic properties, a good liquid desiccant should have low regeneration temperature and viscosity, large saturation absorption capacity, and ought to be nonpoisonous, nonvolatile and nonflammable [14]; from the economic and sustainable views, it should be cheap in price, commonly utilized in industry or daily life, friendly to environment and no bad effect on human health.

Currently, most widely utilized liquid desiccants in LDDS are calcium chloride (CaCl_2), lithium bromide (LiBr_2) and lithium chloride (LiCl_2). Theoretical and experimental researches have been carried out to describe properties of these liquid desiccant solutions, including the specific heat, water vapor pressure and density [20-24]. These studies on the properties of liquid desiccants provides the basic information needed for further research on LDDS.

Serving as a liquid desiccant, calcium chloride is outstanding in its safety characteristics and low cost [25]. Xiong et al. [26, 27] built a two-stage dehumidification system using CaCl_2 as the desiccant, and Saman et al. [28] studied the performance of a dehumidifier with CaCl_2 solution. The well-arranged experiments in their researches proved the effectiveness to use calcium chloride as the liquid desiccant to absorb the moisture from the ambient air.

Compared with CaCl_2 , LiCl and LiBr have higher dehumidification

efficiency [14, 29-32], and therefore, more researchers have chosen the solutions of the latter two as the working fluids. Zhang et al. [33] built up an internally-cooled dehumidifier using LiBr, and analyzed the system performances in simulations and experiments. Fumo et al. [34] carried out a series of inspections on a LDDS with LiCl as the liquid desiccant. Liu et al. [35] concluded that with the same volumetric flow rate, the dehumidification performance of LiCl solution was superior to LiBr. Koronaki et al. [36] compared the system performances with above three liquid desiccants, and their analysis showed that the system utilizing LiCl solution was more stable and predictable than the other two.

Some new attempts on the types of liquid desiccants are made by the researchers, such as mixing solutions [37, 38] and ionic liquids [39, 40]. Mixed liquid desiccants have improved dehumidification efficiency, reduced the material cost and energy consumption. Zhao et al. [32] developed a method to calculate the water vapor pressure of mixing desiccants to select the optimal desiccant mixture. Li et al. [38] divided the liquid desiccant into five groups with different mixing percentage, and experimental results showed that a mass fraction of 31.2% of LiCl and 20% of CaCl_2 gave the best dehumidification effect. Zegenhagen et al. [39] investigated ionic liquid solutions as a replacement of the conventional liquid desiccants. By comparing with the experiments stated in literature, the feasibility of using ionic liquid solution for dehumidification was confirmed.

Although the mixing solution and ionic liquids have superior performances in some aspects, most of them are still in the first stage of investigation. The performance of LiCl is superior to the other two as explained in the literature [41]. Meanwhile, the properties of LiCl solution have been inspected in many works [22, 42, 43]. For instance, the mathematical relations of water vapor pressure, density and specific heat of LiCl solution have all been deducted by Conde [44]. Owing to the good dehumidification performance and detailed properties reported in the literatures, LiCl has been selected as the liquid desiccant of the proposed system in this thesis.

2.3 Improvement of system structure

Besides the research works on liquid desiccants, improvements of the system

structure have attracted many attentions as well. Some are at the system level, such as combining with heat pump or solar energy, and others pay more attention to optimizations in details, such as the packing structure, flow direction and so on.

In the aspects of system level improvements, Xie et al. [45] used a two-stage heat pump cycle to improve the energy efficiency of the system. Niu et al. [46] discussed the interactions between LDDS and heat pump, and proposed that a hybrid system with double-condenser was a reasonable arrangement. Elhelw et al. [47] studied a solar liquid desiccant air conditioning system to evaluate the system performance in a whole year. The relationship between solar energy and regeneration COP was discussed, and the thermal COP reached the maximum in July. Katejanekarn et al.[48] proposed a solar-regenerated liquid desiccant ventilation pre-conditioning system, which confirms the superiority of the regeneration rate compared with dehumidification.

The packing structure is significant in evaluating the heat and mass transfer processes due to the two working fluids contact with each other at their surfaces [49-51]. Potnis [52] compared the random packing and structured packing in their works, and identified that the structured packing materials had better performance. Kavasogullari et al. [53] used polycarbonate panels as the packing materials in their system, and through their investigations, polycarbonate panels were proved effective to be used as a novel packing structure for LDDS.

The contact directions of the working fluids were also well discussed by the researchers [54, 55]. Moon et al.[56] analyzed the mass transfer performance of a cross-flow liquid desiccant dehumidification system with a new empirical correlation. Wang et al.[57] presented an experimental study on the performance of a counter flow liquid desiccant dehumidifier. Other improvements such as the cooling/heating approaches [58-60], multi-stage structures [61, 62], systems with membrane[63-66] and ultrasonic atomization system [67, 68] have all been employed into the LDDS fields these years.

2.4 Modeling of dehumidifiers

Many researches have been carried out to simulate the steady state [69-71] performance of dehumidifier mathematically. Some general methods are finite difference, effectiveness number of transfer units and empirical models [72].

Gandhidasan [73] proposed a simplified finite difference model for LDDS, which was proved to be effective by experimental verifications. Luo et al. [74] developed a volume of fraction model, in which the properties such as density and viscosity were determined by the percentages of air and liquid. Chen et al. [75] proposed a double film model with Effectiveness–NTU relations to describe both the parallel and counter flow dehumidifiers and validated by analytical results. Stevens [76] presented a simplified model based on an assumption of linear relation between saturated enthalpy and temperature, which significantly reduced the computational cost. Bassuoni [77] explained the exited parameters of an adiabatic cross-flow dehumidifier, and the proposed analytical model showed an excellent agreement with the available experimental data. Simplified hybrid models without iterations were developed by Wang et al. [69, 78] which was planned to be utilized in system monitoring and optimization. Experimental results showed the effectiveness of the proposed models. Mesquita et al. [79] analyzed the heat and mass transfer process with three different approaches, and the model with a variable film thickness was proved to have the highest accuracy.

Other than the steady state models, the dynamics of LDDS have also been well studied [74, 80-82]. Diaz [83] developed a two-dimensional mathematical model of the transient heat and mass transfer of a dehumidifier and the dynamic properties were discussed through this model. Coca-Ortegón et al. [84] built up a dynamic model in TRNSYS and proposed some control strategies based on their solar-assisted system. Li et al. [85] developed a dynamic model from the control view based on the heat and mass transfer principles, and was proved to have a good consistency with the experimental data. Wang et al. [86] developed a dynamic model for a counter flow liquid desiccant dehumidifier with experimentally validations and sensitivity analysis.

2.5 Control performances

To sustain a satisfied indoor air quality, the humidity ratio is expected to be regulated automatically to handle different latent loads, and some efforts have been paid on the control issues of the LDDS [87, 88]. Zhao et al. [89] realized the independent control of the temperature and humidity, and the proposed approach was proved to have improved energy efficiency. Ge et al. [90]

presented two control strategies with different operation strategies, and concluded that the solution inlet temperature had a significant impact on the manipulating of the dehumidification rate.

Currently, various approaches have been applied in the air-conditioning field to improve the control performance including the self-turning PID control, fuzzy-PID control, model predictive control and other intelligent methods [91-93]. The control algorithms based on proportional–integral (PI) or proportional–integral–derivative (PID) controllers have been widely used in the regulation of air-conditioning components. Several approaches such as set point filter and anti-windup [94, 95] have been utilized to improve the control performance of this effective control mechanism. Different methods have been proposed to calculate the gains of a PID controller, such as Ziegler–Nichols approach [96], the relative gain based tuning method [97], and the biggest log modulus tuning strategy and gain and phase margins method [98]. Among those applicable selections, fuzzy logical controller is a cost effective nonlinear controller involved with fuzzy heuristic rules derived from the data behavior [99, 100]. The uncertainty problems in PID parameter determination can be mitigated with the fuzzy linguistic rules.

2.6 Summary

This chapter presented an overall review of the literatures on liquid desiccant dehumidification systems. These existed research works have clarified numerous practical problems, and improved LDDS from various aspects. In spite of those solved issues, further investigations on the approaches of utilizing LDDS in the buildings are still needed pressingly. Buildings are large systems with different loads in different zones, as well as many available resources such as piping tubes, waste heat and the solar energy. Hence, an appropriated operating schedule to satisfy the multiple requirements and take full advantage of the building resources is required. This thesis focuses on solving the issues generated from the application of LDDS in large scale. The new operation strategy, modeling of corresponding new facilities, measurement, regulation and optimization of the working solution concentrations, and outlet humidity control are explained correspondingly in the following chapters.

Chapter 3. Modeling and Validation of the Dehumidifier

3.1 Introduction

In the dehumidifier, the desiccant solution absorbs the moisture in the air and becomes diluted, eventually loses the affinity of moisture [101]. Inversely, the regenerator removes the moisture absorbed in the dehumidifier to regain the concentration of working solution. Conventionally, the working solution concentration of dehumidifier is maintained by continuously exchanging solution between dehumidifier and regenerator [102], and the energy utilized for solution transfer increases as the scale of the system becomes large. The regenerator adjusts the operating temperature according to the dehumidification rates. In this situation, the dehumidifier and the corresponding regenerator are required to work at a small concentration gradient. This makes the conventional solution maintaining strategy inapplicable in the distributed manner since different dehumidifiers usually work with different load requirements, and needs specific working solution concentrations to handle different latent loads and requirements.

Considering the necessities of distributed operation and drawbacks of the conventional systems, a buffered integrated dehumidifier is proposed in this Chapter. The continuously exchanging solution is totally avoided with improvement in the structure of the dehumidifier. According to the new operating scheme, the mount of concentrated solution charged into the dehumidifier from the buffer is regulated by a valve to maintain the working solution concentration, and eventually affects the heat and mass transfer process in the dehumidification tower. Therefore, an accurate model is needed to predict the complicate physical processes of this buffered integrated dehumidifier.

In this chapter, the working principle of distributed LDDS is introduced elaborately. The structure improvements of dehumidifier and regenerator are stressed and the working flows of the distributed LDDS are explained in Chapter 3.2. A description of the experimental platform is provided in Chapter 3.3, following by the model development of buffer integrated dehumidifier in Chapter 3.4. The model is validated by experiments as explained Chapter 3.5. Finally, Chapter 3.6 gives a short summary for this Chapter.

3.2 Working principle of distributed LDDS

The distributed operation approach allows LDDS to handle multiple dehumidifiers with one regenerator, which provides a possibility for centralized regeneration of the desiccant solution to be supplied to dehumidifiers running in different places. Furthermore, this method avoids continuously exchange between dehumidifier and regenerator, and the replacement of the desiccant solution only occurs when the limit is reached to improve the energy efficiency. The schematic diagram of the system under study is shown as in Figure 3.1, which is composed of three essential sections, i.e., air treatment, regeneration, and solution storage sections. The air treatment section includes a number of dehumidifiers working in different regions with various humidity requirements. The regeneration section regenerates the diluted solution injected from the weak solution tank to around 10% higher concentration than the highest working solution concentration in dehumidifiers. The solution storage section consists of two storage tanks, one for the diluted and the other one for the strong desiccants which may be placed in different locations, to realize distributed operation to different dehumidifiers to satisfy different dehumidification requirements.

The operating procedure of distributed operating LDDS is briefly described below:

1. In the air treatment section, different dehumidifiers work independently to provide the treated air to different air-conditioned spaces. The moisture migrates from the air to the low temperature strong desiccant solution;
2. There is a criterion for the independent batch operated dehumidifiers, the diluted desiccant solution will be discharged into the weak solution tank once the diluted solution met the pre-set criterion;
3. The regenerator receives the weak solution from the weak solution tank. Since high temperature liquid desiccant possesses a higher water vapor pressure, the moisture migrates towards the regenerating air to make the solution more concentrated;
4. When the pre-set solution concentration is achieved, the strong solution will be transferred to the strong solution storage tank, and ready to be distributed to the dehumidification units.

Figure 3. 1 Diagram of a distributed operating LDDS

In conventional LDDS, strong and weak desiccant solutions continuously exchange between one dehumidifier and one regenerator. This scheme is not applicable in the system under study as one regenerator provides the strong solution to several dehumidifiers working at different concentrations. To facilitate the distributed operation, the dehumidifier is designed as shown in Figure 3.2, where a strong solution buffer and a regulating valve are integrated with a dehumidifier to provide a stable working solution concentration for dehumidifiers. Its operating principles are briefly discussed below:

1. The working desiccant solution in the working solution tank drawn by the circulation pump, pass through the heat exchanger where it is cooled, and then sprayed on top of the packing material;
2. The process air drawn by a fan from the bottom of the dehumidifier is directly contacted with the falling desiccant solution in the packing column in a counter-flow configuration. Since the water vapor pressure

of strong cooled desiccant solution is lower than that of air, the moisture is forced to desiccant solution from the air and the solution becomes diluted;

3. To keep the working solution concentration constant, the strong solution in the strong solution buffer is continuously supplied to the working solution tank, the amount of the strong solution flow into the working solution tank depends on the moisture absorption rate which is controlled by a regulating valve placed in between the two;
4. A hi-low level detector is placed in the working solution tank. When the liquid level of the tank reaches its upper limit, it triggers a pump action to evacuate the working solution to the weak solution tank until the low limit is reached. While the dehumidification functions normally during this solution evacuation process;
5. Similarly, a hi-low level detector is also placed in the strong solution buffer. When the liquid level of the tank reaches its lower limit, it triggers a valve action to fill the strong solution to the strong solution buffer until the high limit is reached. While the dehumidification functions normally during this solution filling process.

Figure 3. 2 Schematic diagram of a dehumidifier

The centralized regenerator described in Figure 3.3 is operated with the following instructions:

1. The ambient air is drawn by a fan and flows through the condenser section of the heat pipe heat exchanger, where it is preheated by the

- heat pipes, and this preheated regenerating air enters the regenerator column from the bottom;
2. The weak desiccant solution preheated by the heat exchanger is sprayed from the top of the regenerator tower by the distributor;
 3. Inside the regenerator, the descending liquid desiccant contact with the process air, the heat and mass transfer occurs due to the temperature and water vapour differences between these two working fluids;
 4. The ascending air passes through the evaporator section of the heat pipe heat exchangers, and transfers its heat to the condenser section to recover the waste energy to improve the regeneration rate;
 5. The temperature of the inlet solution is manipulated according to the desiccant concentration inside the regeneration tank for a most energy efficiency working point;
 6. The regeneration process stops when the pre-set concentration is reached, and the strong solution will be evacuated to the strong solution storage tank, and then distributed to the strong solution buffer of each dehumidifier respect to the dehumidification requirements.

Figure 3. 3 Schematic diagram of a regenerator

3.3 Description of the Experimental platform

The experimental platform is shown in Figure 3.4. The operating method follows the distributed LDDS operating procedure explained in Chapter 3.2.

The dehumidifier tower, which is made of polypropylene, is 1m in height with a cylindrical structure packing with dimension of 0.5m, and the regenerator tower has the same geometric size. A strong solution buffer is installed on top of the dehumidifier to supply strong solution to the dehumidifier during the system operation. A sprayer at the top of column distributes the liquid desiccant solution onto the packing, and a stainless wire mesh is installed to remove the desiccant droplets carried by air flow through the dehumidifier. The cooling source for dehumidifier is chilled water of which the flow rate is regulated by a PID controller. The air and solution flow rate are regulated by the Variable Speed Drives (VSDs) installed on fans and pumps. Lithium chloride (LiCl) is used as the liquid desiccant in this experiment platform.

The mechanical design of the dehumidifier is summarized in Table 3.1

Table 3. 1 Equipment specifications of the dehumidifier

Parameters	Value
Column internal diameter (m)	0.5
Column height (m)	1
Packing height (m)	1
Packing corrugation angle (°)	45
Solution buffer volume (m ³)	0.4
Working solution tank (m ³)	0.4

Figure 3. 4 LDDS experimental platform

1 – fan; 2 – heat exchanger; 3 – heat pipes; 4 – power cabinet; 5 – data acquisition system; 6 – strong solution buffer; 7– working solution tank;

The temperature of the desiccant solution at the inlet and the outlet of the dehumidifier are measured by PT-1000, while the temperature and humidity of the process air at the inlet and outlet of the dehumidifier are obtained from the measurements of a probe type temperature and humidity ratio transmitter. The volume flow rates of the LiCl solution and air are evaluated by a magnetic and a blade type flow sensor. The data of the sensors are collected by the data acquisition system at 1 sample per second. The concentration of LiCl, which cannot be measured directly, is derived from the density measured with the glass hydrometer and respective temperature information. The specifications of sensors are listed in Table 3.2.

Table 3. 2 Specifications of sensors

Sensors	Type	Accuracy	Range
Solution Temperature	PT-1000	0.15 °C	0-100 °C
Air Temperature and Humidity	Probe	0.1 °C ± 0.5 %	0-60 °C ,0-100 %
Solution Flow Meter	Magnetic Flow Meter	±0.5 %	0-50 L/min
Air Flow Meter	Blade	±0.5 %	0 – 600 m ³ / h
Density Meter	Glass Hydrometer	1 kg / m ³	1100-1300 kg / m ³

To evaluate the accuracy of the physical model and soft-sensor, three error indexes are used. They are: Relative Error (RE), Mean Relative Error (MRE) and Root Mean Square of Relative Error (RMSRE), which are expressed as below:

$$RE = \frac{|D_R - D_C|}{D_R} \times 100\% \quad (3-1a)$$

$$MRE = \frac{\sum_{i=1}^M RE_i}{M} \quad (3-1b)$$

$$RMSRE = \sqrt{\frac{\sum_{i=1}^M \left(\frac{D_R - D_C}{D_R} \right)^2}{M}} \quad (3-1c)$$

where D_R is the real value measured from experiment, and D_C is the calculated value by the model.

3.4 Model development

Compared with the conventional dynamic models of dehumidifier regarding

concentration as an uncontrollable variable, the proposed model manipulates the working concentration to describe the concentration profiles during the system operation. Moreover, solution mixing model has been combined, and a latent heat distributed ratio β has been introduced into the model to improve its accuracy.

The working solution tank installed at the bottom of the dehumidifier serves as a blender for desiccant solution from different sources, as shown in Figure 3.5. Four factors will affect the solution concentration, they are: the diluted solution flowing down from the structured packing; the amount of solution remaining in the working solution tank; the flow rate of the strong solution supplied by the strong solution buffer and the flow rate of the working solution transferred from the working solution tank to the weak solution tank. The mass balance of the tank and the solution concentration are described in Eqs. (3-2a) and (3-2b), respectively.

Figure 3. 5 Working solution tank model

$$\frac{dM_s}{dt} = \dot{m}_{s, dilu} + \dot{m}_{s, str} - \dot{m}_{s, mix} - \dot{m}_{s, out} \quad (3-2a)$$

$$\frac{dM_s(1-c_s)}{dt} = \dot{m}_{s, dilu} \cdot (1-c_{s, dilu}) + \dot{m}_{s, str} \cdot (1-c_{s, str}) - \dot{m}_{s, mix} \cdot (1-c_{s, mix}) - \dot{m}_{s, out} \cdot (1-c_{s, out}) \quad (3-2b)$$

where M , $\dot{m}$, c are the mass, mass flow rate, desiccant concentration, and the subscripts s , $dilu$, str , mix and out represent the solution, diluted solution flowing down from the packing column, strong solution from the buffer, fully mixed solution pumped up from the working solution tank for circulation and the solution excavated from the working solution tank, respectively.

Since the properties of the two working fluids vary with the spatial positions, the spatial relations have been simplified by dividing the packing column into N blocks [85], as shown in Figure 3.6. To derive the solution conditions after

interacting with the process air, some assumptions have been applied as follows [69, 85, 86]:

1. Two fluids have a plug flow regime with one dimension inside the dehumidifier;
2. The dehumidifier tower and the working solution tank are adiabatic;
3. No vaporization of liquid desiccant during the whole process;
4. The parameters are constant in radial cross direction of the tower;
5. The desiccant solution pumped out from the working solution tank is fully mixed;
6. The properties of the two working fluids are evenly distributed in each block;
7. Heat and mass transfer occurs inside each block and interacts with adjacent blocks.

Figure 3. 6 Dehumidifier packing column

Supposed that the air and liquid desiccant flowing through each block have a stable volume flow rate, and inside each block, these two working fluids have uniform properties after a sufficient mass and heat transfer as described in Figure 3.7. The $\dot{N}_{H_2O,i}$, $\dot{H}(N_{H_2O,i})$ and $\dot{H}_{as,i}$ represent the mass transfer rate from the air side to the solution side, the heat transfer rate due to the phase change and the sensible heat transfer rate, respectively.

Figure 3. 7 Mass and heat balances in block i

The mass balance of water in the block i are described as Eq.(3-3a) and (3-3b). The left terms in Eq. (3-3a) and (3-3b) are the rates of change of the water amount in these two working fluids in block i. The three terms on the right describe the fluid flows into block i, out of block i and the mass transfer from the other fluids, respectively.

$$\frac{m_{a,i} dd_{a,i}}{dt} = \dot{m}_{a,in,i} \cdot d_{a,in,i} - \dot{m}_{a,out,i} \cdot d_{a,out,i} - V_{a,i} \cdot \dot{N}_{H_2O,i} \quad (3-3a)$$

$$\frac{m_{s,i} d(1-c_{s,i})}{dt} = \dot{m}_{s,in,i} \cdot (1-c_{s,in,i}) - \dot{m}_{s,out,i} \cdot (1-c_{s,out,i}) + V_{a,i} \cdot \dot{N}_{H_2O,i} \quad (3-3b)$$

where d , m , V indicates the humidity ratio, mass and volume, and the subscripts in , out , a , H_2O represent the block inlet and outlet along the flowing direction of each fluid, process air and water, respectively.

The mass transfer rate from the process air to the desiccant solution in block i is explained as Eq. (3-4) [69]:

$$N_{H_2O,i} = K'_G (p_{a,i+1} - p_{s,i-1}^*) \quad (3-4)$$

where $p_{a,i}$, $p_{s,i-1}^*$ and K'_G are the water vapor pressure of process air, surface water vapor pressure of the liquid desiccant solution and the modified mass transfer coefficient, respectively.

By removing the steady-state simplifications proposed in [69], a modified mass transfer coefficient with dynamic properties can be expressed as Eq.(3-5), and the derivation steps are elaborated in Appendix A.

$$K'_G = \frac{\alpha \cdot \hat{c}_1 (\dot{V}_s)^{\hat{c}_3} (\tilde{\rho}_{s,i})^{\hat{c}_4}}{1 + \hat{c}_2 T_{a,in,i-1} (\dot{V}_s)^{\hat{c}_3} (\tilde{\rho}_{s,i})^{\hat{c}_4} (\dot{m}_a)^{\hat{c}_5}} \quad (3-5)$$

of which α , $\dot{V}_s$, $\tilde{\rho}$ are effective contact area, solution volume flow rate and density. The density of the desiccant solution is a function of concentration and temperature [44], and $\hat{c}_1 - \hat{c}_5$ are the parameters needs identification [69, 103].

The energy balance equations for solution and air inside block i are represented as Eq. (3-6a) and (3-6b). The left terms in Eq. (3-6a) and (3-6b) are the rate of energy change of the air and solution in each block, and the three terms on the right of Eq. (3-6a) and (3-6b) are the heat flows into and out of block i , the heat transfer rates between the two fluids, and the latent heat distribution between the two fluids, respectively.

$$M_{a,i} \cdot c_{pa,i} \cdot \frac{dT_{a,i}}{dt} = \dot{m}_{a,in,i} \cdot c_{pa,i} \cdot T_{a,in,i} - \dot{m}_{a,out,i} \cdot c_{pa,i} \cdot T_{a,out,i} - \dot{H}_{as,i} + (1-\beta) \cdot V_{a,i} \cdot \dot{N}_{H_2O,i} \cdot \Delta H \quad (3-6a)$$

$$M_{s,i} \cdot c_{ps,i} \cdot \frac{dT_{s,i}}{dt} = \dot{m}_{s,in,i} \cdot c_{ps,in,i} \cdot T_{s,in,i} - \dot{m}_{s,out,i} \cdot c_{ps,out,i} \cdot T_{s,out,i} + \dot{H}_{as,i} + \beta \cdot V_{a,i} \cdot \dot{N}_{H_2O,i} \cdot \Delta H \quad (3-6b)$$

The T , β and ΔH are the temperature, latent heat distributed ratio and condensing heat of water vapor, respectively. The condensing heat released by the mass transfer increases the temperature of the two fluids with a distributed ratio β in the proposed model. The heat transfer rate between two phases in block i is expressed as Eq.(3-7) [69].

$$\dot{H}_{as} = h' (T_{a,i+1} - T_{s,i-1}) \quad (3-7)$$

A modified heat transfer coefficient including dynamic properties can be expressed as Eq.(3-8), as explained in Appendix A:

$$h' = \frac{\alpha \cdot \hat{c}_6 (\tilde{\rho}_{s,i} \dot{V}_s)^{\hat{c}_8} (\tilde{c}_{ps,i})^{\hat{c}_9}}{1 + \hat{c}_7 \left(\frac{\tilde{\rho}_{s,i} \dot{V}_s}{\dot{m}_a} \right)^{\hat{c}_8} (\tilde{c}_{ps,i} / \tilde{c}_{pa,i})^{\hat{c}_9}} \quad (3-8)$$

of which $\hat{c}_6 - \hat{c}_9$ are the parameters needs identification. The density and the specific heat of the desiccant solution $\tilde{\rho}_{s,i}$ and $\tilde{c}_{ps,i}$ are calculated with the corresponding solution temperature and concentration utilizing the equations explained in [44].

Since there is no packing at the top of the dehumidifier, the air is sufficiently

mixed in this region, which can be calculated with Eqs.(3-9).

$$\frac{m_{a,0} dd_{a,0}}{dt} = \dot{m}_{a,1} \cdot d_{a,i} - \dot{m}_{a,0} \cdot d_{a,0} \quad (3-9a)$$

$$M_{a,0} \cdot c_{pa,0} \cdot \frac{dT_{a,0}}{dt} = \dot{m}_{a,in,1} \cdot c_{pa,1} \cdot T_{a,in,1} - \dot{m}_{a,out,0} \cdot c_{pa,0} \cdot T_{a,out,0} \quad (3-9b)$$

The desiccant solution becomes diluted and flows down to the working solution tank after heat and mass transfer with the process air. The solution stored in the tank is fully mixed and pumped up to the top of the dehumidifier tower and then sprayed down to start a new cycle. The model of a buffer integrated dehumidifier is established by Eqs. (3-2), (3-3), (3-6) and (3-9).

3.5 Experimental validation

To validate the proposed models, experiments are conducted on the LDDS platform introduced in Chapter 3.3. The buffer integrated dehumidifier follows the distributed LDDS operating scheme, and the strong solution buffer and the working solution tank have the same volume of 0.4 m³.

The lumped parameters in Eq.(3-5) and Eq.(3-8) can be identified by the experimental data with Levenberg-Marquardt method [103]. These groups of experiments have been carried out within a concentration interval between 24% and 30%. The temperature and humidity of ambient air is around 22°C to 25°C and 11g/kg dry air to 18g/kg dry air, and the air flow velocity ranges from 1.0 to 2.0 m/s. The values of lumping parameters in mass and heat transfer coefficient denoted as $\hat{c}_1, \hat{c}_2, \hat{c}_3, \hat{c}_4, \hat{c}_5, \hat{c}_6, \hat{c}_7, \hat{c}_8, \hat{c}_9$ are 0.02239, 3.3899, 0.5331, 0.5999, 0.6225, 0.2824, 4.3086, 4.0657, 0.5308 and 0.1538, respectively, and the value of distribution ratio β is 0.25. The predictive accuracy is evaluated with MRE and RMSRE, which are 5.91% and 0.0619 for mass transfer model, and 5.68% and 0.0461 for the heat transfer model.

Several groups of experiments have been conducted to verify the dehumidifier model. The experiments have been carried out in a room with the temperature is around 22°C, and humidity ratio around 12.0 g/kg dry air. To validate the accuracy of this model during the mixing process, two groups of experiments are carried out with different initial concentrations, i.e. 25.5% and 27.5%. The valve connected to the strong solution buffer is fully opened for about 6 mins to let the strong solution flow down from the buffer, and the

system is operating normally during this period. The comparisons between simulation and experimental results are demonstrated in Figure 3.8 and Figure 3.9. From these figures, it can be observed that the predicted outlet air humidity ratio matches the experimental data with a satisfactory accuracy. The deviation between predicted and measured values grows as the working solution concentration increases. One possible explanation is that in the simulation, the variables other than solution concentration are set as constants while in the experiments, the solution temperature and mass flow rate are regulated by controllers, which cannot provide such a stable environment as simulation.

Figure 3. 8 Concentration validation

Figure 3. 9 Concentration validation vs. Outlet air humidity

More validations of the dehumidifier model are conducted to test the model

efficiency with varied inlet solution temperatures. The solution inlet temperature is manipulated as illustrated in Figure 3.10 with the inlet air temperature around 22.3 °C, humidity ratio around 12 g/kg dry air. The initial solution concentration is 27.5%. The MRE and RMSRE in predicting the outlet air humidity ratio are 2.71% and 0.0239, respectively.

Figure 3.10 displays that the predict values respond faster than the experimental measurement data when the inlet solution temperature changed. A possible guess is that some heat capacity is lost during the model simplification. Another point need consideration is that the numerical calculations of the humidity have a slower increasing rate compared with experimental data. According to the modeling explained in Chapter 3.4, this inconsistency between the predicted and measured humidity might due to the errors of modified mass transfer coefficient or the estimations at air mixing stage. MRE and RMSRE in predicting the outlet air humidity ratio and temperature are 3.91% and 0.0409, 2.87% and 0.0222, respectively. Though some errors exist, this model is effective in predicting the response of the dehumidifier with varied working solution concentrations and solution inlet temperatures.

Figure 3. 10 Outlet humidity ratio validations

3.6 Summary

In this Chapter, the working principle of a distributed LDDS for building application has been explicated in details. With a buffer integrated dehumidifier and a centralized regenerator, the proposed scheme could apply the building resources efficiently while satisfying the requirements of occupants. A model describing the heat and mass transfer rate together with the concentration variation profile inside the dehumidifier was developed. The packing column model was built with discretization in spatial to demonstrate the complicated heat and mass transfer process inside the dehumidifier. The mixing process between the strong solution in the buffer and the working solution in the dehumidifier were described by differential equations. The effectiveness of this model was validated by corresponding experiments. By manipulating solution inlet temperature and working solution concentration, the dynamic behavior of this system was studied through simulations and experiments. With the dynamic model presented in this Chapter, the concentration regulation strategy can be further investigated in detail.

Chapter 4. Measurement and Regulation of the Working Solution Concentration

4.1 Introduction

As explained in last Chapter, the distributed operating LDDS allows one regenerator to handle multiple dehumidifier units, which makes it practical to apply the waste heat from chiller plant or solar energy in a centralized form for regeneration. Since multiple dehumidifiers existed in one system working with different solution concentrations, the scheduling of desiccant solutions among the functional components becomes rather important. According to the working principle explained in Chapter 3.2, the working solution concentration in the dehumidifier and regenerator should be measured and controlled to realize this new operating scheme.

To measure the working solution concentration, market available online sensors are usually not suitable due to the high economic cost and the complicated operational procedure. In an operating condition with corrosive substance, the reliability of the sensors decreased as the usage hour accumulating, re-calibration is needed which will interrupt the system operation. Moreover, the complex mathematical form of the commonly utilized liquid desiccant solution properties [44] increase the difficulty in solving the solution mathematically. An alternative method to solve this problem is developing a soft-sensor to obtain the values of the unmeasurable variables from the existing monitoring and control system, so that the concentration can be acquired with no additional cost. Yan et al. [104] designed a soft-sensor by genetic algorithms and group decision making methods, which provided a convinced stability and accuracy for the collection of online dissolved oxygen concentration values. Fortuna et al. [105] designed a soft-sensor to measure gasoline concentration, which was validated to have an instant response on the input variations, and was suitable for both monitoring and control. Jin et al. [106] developed a method for multi-model soft sensing modeling based on time variant process.

ANFIS integrates the advantage of learning in artificial neural network and employing fuzzy reasoning, which makes it an appropriate choice in soft-sensor development [107]. Chong et al. [108] designed a soft-sensor for dye concentration, and Ghiasi et al. [109] developed a soft-sensor for CO₂

concentration detection in a CO₂ capture process, both utilizing ANFIS framework. The fuzzy rule identification is important in ANFIS development. The use of genetic algorithm (GA) in fuzzy system development attracts greater research effort than other approaches [110-112]. GA, a stochastic optimization technique [113], can optimize the ANFIS structure. Dahal et al. [112] presented a genetic algorithm (GA) based learning approach for ANFIS. Tahmasebi et al. [114] derived a method to obtain the best parameters of ANFIS from GA. These intelligent methods provide optional approaches for the soft-sensor design and structure optimization.

In dehumidifiers, stable working concentration is a pre-request criterion to guarantee a stable dehumidification rate, especially when the dehumidifier is in a distributed operation mode. Thus, to apply LDAC in a more intelligent way needs a concentration regulation strategy. As described in Chapter 3.2, the dehumidifier is integrated with a buffer, and the mount of concentrated solution stored in the buffer is regulated by a valve to charge desiccant into the dehumidifier. Soft-sensors collect the real-time concentrations in the dehumidifier and regenerator, and provide the information for the regulation strategy of the working solution concentrations. The constraints of the concentration regulation strategy are subjected to the physical limitations and the safety operating criterions of a distributed LDDS, as explained in Chapter 3.4.

In all, this Chapter covers the issues related to the measurement and regulation of desiccant solution concentration. In Chapter 4.2, the model-based soft-sensor with GA optimized ANFIS structure is developed, and then, the well-tuned soft-sensors for dehumidifier and regenerator are validated respectively in Chapter 4.3. The concentration regulation method is explained in Chapter 4.4 and following by model-based simulations in Chapter 4.5. The experimental validations are described in Chapter 4.6. Chapter 4.7 briefly summarizes the contents of this chapter.

4.2 Development of the concentration soft-sensor

The proposed soft-sensor has a structure illustrated as Figure 4.1, which is composed of a mass transfer model and an optimized ANFIS. The input variable numbers are reduced by the models elucidated in Appendix B, and the

fuzzy rule mapping is improved with GA as demonstrated in Chapter 4.2.1, and Chapter 4.2.2 gives a clarification about the connections between the physical model and the ANFIS framework.

Figure 4. 1 Structure of the soft-sensor

4.2.1 Soft-sensor structure with GA optimized ANFIS

A basic ANFIS framework has a total of five layers, and the topology structure is described as in Figure 4.2. Each layer represents a specific function in this system: the first and second layers transfer the crispy input into linguistic variables; the third layer expresses the fuzzy rules; the fourth layer is the weight of each rule; and the fifth layer is aggregated to calculate the output values.

The soft-sensor has been developed with two major steps: ANFIS structure optimization and artificial neural network parameter tuning, which will be discussed in the following sub-sections:

Figure 4. 2 Architecture of ANFIS

a) GA optimized ANFIS structure

The proposed soft-sensor converts a series of complicated physical relations

into a Multi-Input Single-Output structure with ANFIS framework. ANFIS is an intelligent structure which can achieve high accuracy if well trained. However, for an online soft-sensor, the predictive accuracy is not the only criterion to evaluate its performance, since high accuracy requires a complicated structure, and increases the computational load. Therefore, GA is introduced to optimize this rule number and generate the corresponding fuzzy mapping rules to develop an accurate soft-sensor with a simplified structure [112].

Encoding:

Each input or output is corresponding to a gene. For a soft-sensor with m inputs and 1 output, there are $m+1$ genes locating on the same chromosome. An example chromosome for a 4 inputs and 1 output soft-sensor is depicted in Figure 4.3.

0010	1000	1001	0001	0001
0011	1000	0010	1000	0101
0001	0001	1001	0100	0100
1000	0111	1000	0101	1000

Figure 4. 3 An example of chromosome

The chromosome showed in Figure 4.3 is the binary-coded decimal encoding result of $\{0.2318 \ 0.8817 \ 0.9298 \ 0.1845 \ 0.1548\}$. These genes indicate the effective ranges of the centers during the data clustering processes [115] and the clustering results further determine the fuzzy rule mappings. The fuzzy relationships are built up from the clustering results to form a preliminary ANFIS structure [116, 117].

Objective Function:

A constraint objective function is proposed to optimize this structure with enough but not redundant cluster numbers. The objective function is expressed as Eq. (4-1), including the rule number function, the constraint function and the extinction function:

$$\begin{cases} Objfun(i) = Rulenum(i) + ConFun(i), & ConFun(i) \leq \varepsilon \\ Objfun(i) = ExticFun + ConFun(i), & ConFun(i) > \varepsilon \end{cases} \quad (4-1)$$

where i indicates the i^{th} chromosome in the current generation.

The rule number function is:

$$Rulenum(i) = \max(n_{1,i}, n_{2,i}, \dots, n_{j,i}, \dots, n_{m,i}) \quad (4-2)$$

where $n_{1,i}$, $n_{2,i}$, ..., $n_{j,i}$, ..., $n_{m,i}$ are the cluster number for each input obtained by the modified mountain clustering algorithm [115] utilizing the genetic information carried by the i^{th} chromosome. The maximum value among these results determines both the neuron number of layer 4 and the fuzzy rule number of the i^{th} ANFIS structure.

Another factor in the objective function is the constraint function:

$$\text{ConFun}(i) = \sum_{j=1}^N (c_j - c_{e,j})^2 \quad (4-3)$$

of which c_j is the soft-sensing result and $c_{e,j}$ is the value gained from the measurement. N is the number of data samples used to test the model accuracy with of i^{th} ANFIS structure. In the objective function, the constraint function is a term to distinguish among the structures with the same fuzzy rule number but different connections and assist the algorithm to choose the one with highest accuracy.

The extinction function is:

$$\text{ExticFun}(i) = \text{Max}(n_1, n_2, \dots, n_i) \quad (4-4)$$

where n_1 , n_2 , ..., n_j , ..., n_N are the largest rule number value in the current generation.

If the constraint function value of Eq. (4-3) is within the tolerance limit ε , this structure is regarded as acceptable, the sum of Eq. (4-2) and Eq. (4-3) which will be assigned to the objective function. If constraint function value is beyond the acceptable range, a label will be given to the objective function and the value of the objective function change to the sum of the extinction function and constrains function.

Population and GA operators:

The initial population of the chromosomes is generated randomly, and all the chromosomes from the population are ranked based on the objective function values evaluated from Eq.(4-1). Those intolerant structures with complex structures or unsatisfactory accuracy will become less important or will be eliminated in the offspring generations. The offspring in the next generation is generated from the parents by evolution, including selection, crossover and mutation operators to the chromosomes until the maximum number of generations is reached or the objective function reaches its tolerance.

b) Neural network parameter tuning

Besides the basic framework, the weight parameters of ANFIS need to be tuned. These parameters are calculated by the backpropagation algorithm combining with the least square method [118] on the determined optimized structure. The aim of this tuning is to improve the accuracy based on the optimized ANFIS structure obtained by minimizing the error explained in Eq. (4-5):

$$Error = \sum_{i=1}^S (c_i - c_{e,i})^2 \quad (4-5)$$

where S is the sample size of the training database, con_i is the soft sensing result, and $con_{e,i}$ is the concentration value calculated with the desiccant density and corresponding desiccant solution temperature obtained from the offline measurement [44].

The antecedent and consequent parameters, which are the connection weights between the nodes in layer 1 and 2, and layer 4 and 5, are the most important parameters need to be trained. The values of antecedent and consequent parameters can be obtained by directly minimizing performance criteria as Eq. (4-6).

The adjustment of the connection weights $w_{j,j-1}$ is calculated as follows [119]:

$$\Delta w_{j,j-1} = -\eta \frac{\partial error}{\partial w_{j,j-1}} = \eta \delta_j input_j \quad (4-6a)$$

$$\delta_j = -\frac{\partial error}{\partial v_j} = -e_j \phi'_j [v_j] \quad (4-6b)$$

where η is the learning-rate parameter of the back-propagation algorithm, and δ_j is the local gradient, ϕ_j the nonlinear function involved with layer j , v_j is the weighted sum of layer j with the weight $w_{j,j-1}$.

This tuned structure is then validated subsequently by comparing the soft-sensing concentration values with the off-line calculated concentration values.

In summary, the algorithm for GA facilitated ANFIS soft-sensor is provided as follows:

- Step 1:** Initializing the population which consists of random generated chromosomes within the constraints;
- Step 2:** Encoding the chromosome to binary structures;
- Step 3:** Clustering the experimental data based on the clustering information carried by the chromosome;
- Step 4:** Determining the ANFIS structure from the cluster number and centers obtained in Step 3;
- Step 5:** Evaluating the error the structure obtained in Step 4 by minimizing the objective function with the model accuracy constraints;
- Step 6:** Ranking the chromosomes by the objective function values and generate the offspring based on the ranking results;
- Step 7:** Repeating from Step 2 until the termination criterion is satisfied;
- Step 8:** Decoding the optimal chromosome and determine the ANFIS structure;
- Step 9:** Tuning the weight parameters of the backpropagation algorithm combining with the least square method;
- Step 10:** Validating the results of the soft-sensor.

The flow chart of the developed soft-sensor is illustrated in Figure 4.4.

4.2.2 Reducing input variables by model information

GA is applied to reduce the redundant fuzzy clusters to simplify the ANFIS structure. Further simplification of the structure is to reduce the numbers of input variable which will reduce computational loads in both soft-sensor development and application. In the development of soft-sensor, excessive inputs increase the difficulties in data clustering, structure optimization, and the training-required for parameters. In the soft-sensor application phase, more input variables result more parameters to be stored and heavier computational loads during classification procedures in each round. For example, assume there is an ANFIS with a fuzzy rule number n_{fm} , reducing one input variable means reducing n_{fm} linear parameters, $2 n_{fm}$ nonlinear parameters and at most reducing $2 n_{fm}$ comparison operations in a single round of calculation.

The physical models developed in Appendix B can be utilized to reduce the input dimension of the ANFIS frame to further simplify the soft-sensor structure. By substituting Eq. (B-1) into Eq. (B-5), we have:

$$p_{s,in}^*(c_{D/R}, T_{s,in}) = p_{a,in} - \frac{HR_{a,in}(T_{a,in} \cdot RH_{a,in})\dot{m}_a}{V \cdot \frac{\hat{c}_1(\dot{m}_s)^{\hat{c}_3}}{1 + \hat{c}_2 T_{a,in}(\dot{m}_s)^{\hat{c}_3}(\dot{m}_a)^{\hat{c}_4}}} + \frac{HR_{a,out}(T_{a,in} \cdot RH_{a,out})\dot{m}_a}{V \cdot \frac{\hat{c}_1(\dot{m}_s)^{\hat{c}_3}}{1 + \hat{c}_2 T_{a,in}(\dot{m}_s)^{\hat{c}_3}(\dot{m}_a)^{\hat{c}_4}}} \quad (4-7)$$

where $p_{s,in}^*(c_{D/R}, T_{s,in})$ is defined in Eq. (B-4). The values of $p_{a,in}$ and HR can be calculated from Eq. (B-3a) and (B-5b).

Figure 4. 4 Flow chart of ANFIS structure determination

Then, eight variables can be measured directly by the sensor system installed in the dehumidifier/regenerator, which are: the inlet and outlet air temperatures and relative humidity values; mass flow rates of air and desiccant solution; solution inlet and outlet temperature. From Eq. (4-7), it is known that the solution concentration is a function of 7 independent variables, denoted as $T_{s,in}$, $T_{a,in}$, $\varphi_{a,in}$, $T_{a,out}$, $\varphi_{a,out}$, $\dot{m}_a$, $\dot{m}_s$, and the desiccant concentration can be calculated from these measurable variables.

Define the second and third terms on the right-hand side of Eq. (4-7) as:

$$G_1 = -\frac{\dot{m}_a HR_{a,in} \left(1 + \hat{c}_2 T_{a,in} (\dot{m}_s)^{\hat{c}_3} (\dot{m}_a)^{\hat{c}_4}\right)}{V \cdot \hat{c}_1 (\dot{m}_s)^{\hat{c}_3}} \quad (4-8a)$$

$$G_2 = \frac{\dot{m}_a HR_{a,out} \left(1 + \hat{c}_2 T_{a,in} (\dot{m}_s)^{\hat{c}_3} (\dot{m}_a)^{\hat{c}_4}\right)}{V \cdot \hat{c}_1 (\dot{m}_s)^{\hat{c}_3}} \quad (4-8b)$$

Consequently, four intermediate variables, $p_{a,in}$, G_1 , G_2 and $T_{s,in}$, are selected as the input variables of the ANFIS. The simplification is visualized as Figure 4.5.

Figure 4. 5 Soft-sensor input variables reduction

This model-based simplification decreases the input dimension from 8 to 4 to simplify the ANFIS framework, which reduces the computational loads of the soft-sensor in development and application.

4.3 Experimental validation of the soft-sensors

The measured concentration of desiccant solution, which cannot be acquired directly, is derived from the density measured with the glass hydrometer and respective temperature information with specifications listed in Table 3.2. The market available online concentration/density sensors for caustic solution are expensive, and the price of one customized on-line concentration sensor is significantly higher than the total costs of all the other sensors installed in the dehumidifier for operation monitoring. Therefore, soft-sensor is the wise choice to apply in the distributed LDDS to monitor the concentration information.

The soft-sensors of the dehumidifier and regeneration sides are designed to

detect the working solution concentrations of two main working components. The dehumidification side requires high accuracy in concentration measurement, and the regeneration side monitors the concentration to determine regenerator stopping timing. These two types of soft-sensors are validated separately from different aspects based on the individual working requirements. The regenerator soft-sensor focuses on the simplification of the structure while the dehumidifier validates the measurement accuracy more comprehensively in various environments.

4.3.1 Validation of the regenerator soft-sensor

The experiments are performed in the following conditions:

- 1) The inlet air has a humidity ratio of 11-18 g/kg dry air and a temperature in the range of 20-25°C;
- 2) The same initial solution concentration of 26% for each round of the test;
- 3) No solution exchanging during the whole regeneration period;
- 4) The regeneration process ends automatically at the desiccant concentration at the pre-set concentration of 38%.

The data samples are acquired in the condition with inlet solution temperatures in between 30°C-55°C and mass flow rates in the range of 0.4kg/s-0.9kg/s. Four databases have been built up for mass transfer model validation, parameter training, soft-sensor validation and ANFIS structure optimization.

The lumping parameters in Eq. (4-7) are identified with the mass transfer model database. This model is trained with the data samples covering the whole regenerator operating range. The values of $\hat{c}_1, \hat{c}_2, \hat{c}_3, \hat{c}_4$ are 0.0100, 8.001, 5.029, 4.9843, respectively. The relative errors of the model are illustrated in Figure 4.6 and the MRE and RMSRE are 5.70% and 0.01689, respectively.

Figure 4. 6 Relative error of regeneration mass transfer model

To evaluate the effectiveness of the soft-sensor and simplification methods, three different structures are trained and verified. The first structure is the original data driven ANFIS; the second one is model-based ANFIS, utilizing the mass transfer model demonstrated in Appendix B for the input variable simplification; the last one optimized the model-based ANFIS with the strategy explained in Chapter 4.2. These three models are denoted as ANFIS, Mo-ANFIS and Mo-Opt-ANFIS in the following statements, and the accuracy and simplicity of these models are discussed in this section.

For the original data driven ANFIS, the eight inputs are the mass flow rate of air and solution, the solution outlet and inlet temperature, the inlet air humidity and temperature and the outlet air humidity and temperature, and the fuzzy membership functions are depicted in Figure C1. The model predicted and measured concentrations scatter over the regenerator operating range as described in Figure 4.7, and the results show a good accuracy of this model from the errors shown in Figure 4.8. This structure has 15 fuzzy rules generated from the clustering results and totally 375 parameters. With this meticulous structure, the relative errors are kept below 1.2%, and the MRE and RMSRE values are 0.5210% and 0.0071, respectively.

Compared with the original data-driven ANFIS, the input dimension of the model-based ANFIS (Mo-ANFIS) decreases from 8 to 4, and the number of total parameters decreases to 156. From Figure 4.9 and Figure 4.10, it can be observed that the soft sensing concentration values acquired by this model are

consistent with the measured values. The relative errors are less than 3%, and the MRE and RMSRE are 0.7472% and 0.0103, respectively. The fuzzy membership functions are described as Figure C2.

Figure 4. 7 Regenerator soft-sensor validation (ANFIS)

Figure 4. 8 Regenerator soft-sensor model errors (ANFIS)

Figure 4. 9 Regenerator soft-sensor validation (Mo-ANFIS)

Figure 4. 10 Regenerator soft-sensor errors (Mo-ANFIS)

The GA serves as a method to further simplify the structure of the model-based ANFIS. The randomly generated initial population of GA has 500 chromosomes, and each determines a particular ANFIS structure. Every structure is evaluated by the constraint function with 20 data samples from random selections. The top-ranked chromosomes are selected to generate the new generation of offspring with a mutation probability of 0.8% and a two-point mutation method. The maximal generation number is 100, and the tolerance of the change between two generations is 10^{-6} . The optimal ANFIS structures selected by GA is generated from a chromosome with a gene series as 0.2004 0.3019 0.2031 0.2143 0.3162, and the corresponding values of Eqs. (4-2), (4-3) and (4-4) are 6, 0.0301 and 13, respectively. The validation results

of this GA optimized model-based ANFIS (Mo-Opt-ANFIS) are described in Figure 4.11 and Figure 4.12 and the MRE and RMSRE are 1.0230% and 0.1327, respectively. The optimal fuzzy membership functions obtained from GA are described as Figure C3.

Figure 4. 11 Regenerator soft-sensor validation (Mo-Opt-ANFIS)

Figure 4. 12 Regenerator soft-sensor errors (Mo-Opt-ANFIS)

The values of performance indices and the structure characteristics are summarized in Table 4.1. Compared with the original ANFIS structure, Mo-ANFIS model reduces 58.4% of the total parameters, and the fuzzy rule number also decreases from 15 to 12. The parameter number of the Mo-Opt-ANFIS decreases 50% after GA optimization compared with the Mo-ANFIS model, and reduces 70.2% respects to the original ANFIS with only a slight loss of accuracy.

This soft sensing model is developed for the concentration detection in a centralized regenerator, of which the solution temperature is between 30°C and 55°C, and the desiccant concentration is in the range of 26%-38%.

Table 4. 1 Performance indices of different methods

Model	Input	N_{fm}	Nonlinear	Linear	TotalPara	MRE	RMSRE
ANFIS	8	15	240	135	375	0.5210%	0.0099
Mo-ANFIS	4	12	96	60	156	0.7472%	0.0103
Mo-Opt-ANFIS	4	6	48	30	78	1.0230%	0.0133

4.3.2 Validation of the dehumidifier soft-sensor

The testing is carried out in the conditions:

- 1) inlet air temperature at 20-25°C and humidity ratio 11-18 g/kg dry air;
- 2) each round of experiment is started with the same initial solution concentration of 30%;
- 3) no strong solution is fed into the working solution tank from the strong solution buffer during the whole testing period ending at the solution concentration 24%.

During the system operating, the inlet solution temperature is manipulated between 12°C-20°C and the desiccant mass flow rate is varied between 0.2kg/s-0.6kg/s independently to collect and record the data samples in different working conditions.

Four databases specify to the dehumidification side are constructed with the data samples collected in different concentrations and operating conditions, and then utilized for physical model training/validation, ANFIS structure optimization, weight training and soft-sensor validation, respectively.

The lumping parameters of mass transfer coefficient for dehumidifier model in Eq. (4-7) are identified with the data from physical model database by Levenberg–Marquardt method. With a wide operating range of experimental data, this physical model is able to provide an accurate prediction in the dehumidifier working conditions. The values of the $\hat{c}_1, \hat{c}_2, \hat{c}_3, \hat{c}_4$ of the mass transfer coefficient are 0.1249, 2.356, 2.3500, and 0.7949, respectively. The

relative errors of the physical model are illustrated as in Figure 4.13 and Figure 4.14 and the MRE and RMSRE are 1.75% and 0.0033, respectively.

Figure 4. 13 Physical model validations

Figure 4. 14 Physical model errors

During the optimization, the ANFIS structure is firstly determined by a chromosome from the initial population. The initial population is generated randomly with a size of 500. The generated data are sufficient to cover the ranges and data distributions. The structure determined by the randomly generated chromosome is evaluated with 20 randomly selected data samples. The performance of each structure is calculated by the constraint function, Eq. (4-3), to test its accuracy, in which N equals 20. From the ranking results of objective function values, the top-ranked chromosomes are selected to generate the new generation of offspring. A mutation probability of 0.8% is considered to

analyze the sensitivity of performance with a two-point mutation method.

The optimized chromosome selected by GA is 0.3887 0.4841 0.4233 0.2082 0.1858, which specifies a scope of influence of the cluster centers for each gene. The optimal fuzzy rules obtained from GA are described as Table C.1 in Appendix C. The numbers in Table C.1 indicate the cluster groups, of which the cluster centers are expressed in Table C.2 in the Appendix C, and the membership functions are Gaussian type membership functions. The values of the rule number function, extinct function and constraint function of this optimal chromosome are 14, 19, and 0.31, respectively.

Compared with the original data driven ANFIS structure without any simplification, the optimized ANFIS framework reduces 40.9% of the total parameter numbers, which indicates a significant reduction of computational loads. After the structure is determined, the weight of each fuzzy rule is trained to improve the accuracy of this ANFIS. Training error of ANFIS decreased to less than 0.03.

Figure 4.15 and Figure 4.16 shows the comparison results of desiccant concentration values between the soft-sensor outputs and the indirectly measured values and the respective REs. All the relative errors are below 0.4% and above 90% are below 0.3%. The MRE and RMSRE are 0.8332% and 0.007335, respectively. It is found that the soft-sensing results are consistent with the indirectly measured concentration values.

Figure 4. 15 Dehumidifier soft-sensor validations

Figure 4. 16 Dehumidifier soft-sensor errors

The experiments are conducted multiple times to form a sufficient database to validate this soft-sensor with various experimental situations. Based on the statistical data, the uncertainties of the measured data are calculated and the error bars are given in Figure 4.17.

Figure 4. 17 Dehumidifier soft-sensor accuracy analysis

The efficiency of this soft-sensor is further verified in a 140mins experiment following the batch operation scheme. During the experiment, the inlet air temperature is around 22°C, the humidity ratio is around 14 g/kg dry air, and the mass flow rate of air and desiccant solution are regulated at 0.2064 kg/s and 0.39kg/s, respectively. The temperature of inlet solution, which has been

regarded as the most impacting factor on the dehumidification rate [90], is manipulated between 12°C and 20°C to test the performance of the soft-sensor in working conditions with disturbances. As described in Figure 4.18, it turns out once again that the predictive results show a good agreement with the measured data, and the variations of inlet solution temperature have no observable influence on the predictive accuracy of the proposed soft-sensor.

Figure 4. 18 Soft-sensor efficiency in batch operation

More experiments are conducted to test the performance of this soft-sensor in a solution mixing process. The regulation valve is fully open for 6 minutes to charge the strong solution into the working solution tank from the strong solution buffer. The concentration of strong solution is 34% and the initial concentration of working solution is 25.5%. The dehumidifier is in the normal operating mode, and the effectiveness of soft-sensor is validated in the mixing process as illustrated in Figure 4.19.

Figure 4. 19 Soft-sensor efficiency in solution mixing process

Qualitative comparisons have been conducted to explain the priority to apply a soft-sensor in the distributed LDDS.

Table 4. 2 Comparisons of different sensing types

Sensor Type	Installation	Cost	Continuous measurement
Off-line	Easy	Low	No
On-line	Difficult	High	Yes
Soft-sensor	No additional cost	No additional cost	Yes

This soft-sensor is specifically designed for dehumidification working solution concentration detection and is limited to the working conditions of a dehumidifier in distributed LDDS with a target concentration range between 24%~30%.

4.4 Regulating method of working solution concentration

A concentration regulation strategy is developed to stabilize the working solution concentration of the dehumidifier. The supplied amount of strong solution is determined by the flow rate of the strong solution and the opening duration of regulating valve. By manipulating the opening duration respect to the mass flow rate of strong solution, the working solution concentration is confined within the required range, and the inlet and outlet air humidity are monitored as a feedback of this concentration regulation strategy.

4.4.1 Calculation of strong solution flow rate

As described in Figure 4.20, a regulating valve is installed in the tube connecting the strong solution buffer and working solution tank. The volume of the strong solution charged into the dehumidifier can be calculated with the solution flow rate and valve opening duration. The flow rate of strong solution is determined by the liquid level in the strong solution buffer and the hydraulic resistance the solution overcomes, as explained Eq. (4-9). Both sides of Eq.(4-9) represent the pressure value at the entrance point of the working solution tank.

The first term on the left side of Eq. (4-9) is the friction resistance due to momentum transfer to the solid walls, and the second term is local resistance caused by dissipation of mechanical energy at the position of the ball valve and tuning tubes [120].

$$\frac{\lambda L}{D} \cdot \frac{\rho v_{str}^2}{2} + (\zeta_{turn1} + \zeta_{turn2} + \zeta_{valve}) \frac{v_s^2 \rho}{2} = \rho g (h_1 + h_2) \quad (4-9)$$

where the ρ , h_1 , h_2 , L , D and v_s are the density of strong solution, the height of liquid in the strong solution buffer, the vertical height of the connecting tube between the two tanks, the tube length, tube diameter and the velocity of the strong solution. ζ_{turn1} , ζ_{turn2} and ζ_{valve} are the coefficient of local resistance of two ninety-degree bends and one ball valve, and λ is friction coefficient, can be expressed as $\lambda = 0.3164 / \text{Re}^{0.25}$, where $\text{Re} = \frac{\rho v_s D}{\mu}$. Simplified from Eq.(4-9), the velocity of the strong solution flow can be estimated with the solution of Eq.(4-10):

$$a_1 v_{str}^2 + a_2 v_{str}^{1.75} - a_3 = 0 \quad (4-10)$$

where $a_1 = \zeta_{turn1} + \zeta_{turn2} + \zeta_{valve}$, $a_2 = \frac{0.3164 \mu^{0.25} L}{\rho^{0.25} D^{1.25}}$ and $a_3 = 2 \rho g (h_1 + h_2)$.

The volume flow rate is:

$$\dot{V}_{str} = v_{str} \cdot \pi (D/2)^2 \quad (4-11)$$

Figure 4.20 Geometric connections between dehumidifier and buffer

4.4.2 Calculation of valve opening duration

The moisture absorbed from the air accumulates and dilutes the concentration of the desiccant solution in the dehumidifier. In a short period of time, the concentration does not decrease much due to the large amount of stored solution in the working solution tank, and this suggests the possibility of manipulating the regulating valve in an intermittent method within a time interval t . The following equation is obtained by the mass conservation principle:

$$c_{upper} = (c_{s,mix} \rho_{s,mix} V_D + c_{str} \rho_{str} \dot{V}_{str} t) / \left(\rho_{s,mix} V_D + \rho_{str} \dot{V}_{str} t + \sum_{i=0}^N \dot{m}_{D,i} t \right) \quad (4-12)$$

where c_{upper} , V_D , $\rho_{s,mix}$, ρ_{str} are the upper boundary of the working solution concentration, volume of solution remains in the working solution tank, the density of the working solution and strong solution, respectively.

The solution concentration in the working solution tank c_w or $c_{s,mix}$ in Eq.(12) and regenerator tank c_s are measured by the concentration soft sensors [121, 122] of each side. $\sum_{i=0}^N \dot{m}_{D,i} t$ is the moisture absorbed in dehumidifier in a period of t , and $\dot{V}_{str}$ is the volume flow rate of strong solution calculated using Eq. (4-11). Some variables relevant to time are simplified as constants in a short period of time.

In this strategy, one vital step is to calculate the proper working solution range. The value of c_{upper} is the upper boundary of the acceptable working

solution concentration and the concentration lower than c_{lower} triggers the supplement of strong concentration. The working solution concentration ranges can be obtained by the system operating constraints in Eq. (4-13).

$$f^{-1}(d_{sp}, T_{s,in,mid}, m, t_0) - \varepsilon_{cm} \leq c \leq f^{-1}(d_{sp}, T_{s,in,mid}, t_0) + \varepsilon_{cm} \quad (4-13a)$$

$$f^{-1}(d_{upper}, T_{s,in,lower}, t_0) \leq c \leq f^{-1}(d_{lower}, T_{s,in,upper}, t_0) \quad (4-13b)$$

$$h_{lower} \leq (V_D - \dot{V}_{tsf}t + \dot{V}_{str}t) / S \leq h_{upper} \quad (4-13c)$$

where the subscripts *sp*, *upper*, *lower* and *mid* means the set point, upper boundary, lower boundary and the median value, respectively. The $\dot{V}_{tsf}$ and S are the volume flow rate of evacuation transfer, and the cross section of the working solution tank, and ε_{cm} is the acceptable error in concentration, and function f signifies dehumidifier model explained in Chapter 3.4.

The inequalities Eq. (4-13a) and (4-13b) offer two choices of the concentration working ranges. Eq.(4-13a) refers to a criterion obtained from the concentration measurement accuracy, and the Eq.(4-13b) determines the working solution concentration ranges by considering the inlet solution temperature. Both Eq.(4-13a) and (4-13b) can be applied in this strategy. The solution level is regulated as Eq. (4-13c) for the purpose of continuous operation.

Denoted $(c_{upper} - c_{s,mix})\rho_{s,mix}V_D$, $c_{upper} \sum_{i=0}^N \dot{m}_{D,i}$ and $(c_{str} - c_{upper})\rho_{str}$ as s_1 ,

s_2 , s_3 , and the open period can be calculated with Eq.(4-14):

$$t = \frac{s_1}{s_3 \cdot \dot{V}_{str} - s_2} \quad (4-14)$$

When the volume of the solution in the working solution tank exceeds the upper limit, part of the solution in the working solution tank will be transferred to weak solution tank to wait for regeneration. The regulating valves will be closed before the excavating process starts and the valve opening duration will be recalculated according to the new operating conditions.

4.4.3 The monitor of humidity

The inlet and outlet humidity ratios are monitored as feedbacks of the

concentration regulation strategy. The mass transfer rate can be roughly estimated during the time intervals to ensure no significant disturbance occurs. If the load has a sharp increase, the strategy will generate a new round of valve opening adaptively, while a sharp decreasing of the latent load needs the monitoring system to recalculate the opening duration to avoid the overcharge of concentrated solution.

The circulation pumps and transfer pumps need certain liquid level to start normally, and those criterions are determined in the stage of system design. The liquid levels are monitored to guarantee the operating safety in case the solution volume exceeds the tank capacity or below the necessary levels. These thresholds and regulation parameters are set and tuned in simulations based on the model proposed in Chapter 3.4.

The flow chart of control strategy is shown as Figure 4.21. The controller receives a humidity set point, and then calculates the corresponding working solution concentration. There are several methods to determine the mapping between outlet air humidity and working solution concentration, such as utilizing empirical data, mathematical model in Chapter 3.4 and energy optimized working pairs which will be elucidated in the next chapter. To reduce the computational load, a table mapping the required concentration and outlet air humidity has been generalized in advance. The controller regulates the mixing processes to guarantee the working solution concentration, while monitors the liquid amount in all the storage facilities to ensure the safeness and continuity of the system operation.

This regulation strategy is effective in balancing the concentration lost brought in by the batch operating mechanism, and able to manipulate the working solution concentration to increase to a new set point by responding the interrupts from the occupants. Furthermore, the strategy also can be used when the attached buffer is filled with weak solution, which means the working solution concentration can be blend to any requirements according to the requirements or environment conditions.

Figure 4. 21 Flowchart of the control strategy

4.5 Simulation of the regulation strategy

To fully assess the performance of this control strategy, a series of simulations have been carried out. The performances of this strategy under the step changes of the inlet solution temperature and inlet air humidity are compared and analyzed using Matlab R2010b on a computer with Intel Core i7-3770 CPU @3.40 Ghz and 8.00 GB memory.

Case 1: Simulation without disturbances

No disturbances have been introduced in this case, and the performance is typically associated with the change of working solution concentration in the dehumidifier over the operating time. To control the outlet air humidity at 7.0g/kg dry air, the target working concentration is set as 26.3% within an acceptable error of $\pm 0.3\%$. The upper concentration is 26.6% and lower

concentration is 26.0% as explained in Eq. (4-13a). The inlet air temperature is around 22.3°C, and the humidity ratio is approximately 12.0 g/kg dry air. The first figure of Figure 4.22 shows the valve opening times and duration in the simulation. The regulating valve opens when the concentration reaches the lower concentration boundary, and the flow rate decreases over time as the liquid level in the strong solution buffer decreases. The Figure 4.22 reveals that the concentration decreases around 2.1% in the four-hour simulation without regulation and this strategy successfully maintains the working concentration at around 26.3%.

Case 2: Simulation with step change of solution inlet temperature

This case is carried out to analyze the impact of solution inlet temperature on the performance of this regulation strategy. In this simulation, a step input of the solution inlet temperature increasing from 16.5 °C to 17.2 °C is created at the 120min. As illustrated in Figure 4.23, the control strategy successfully stabilizes the solution concentration by adjusting the opening duration of the regulating valve. The decrease of solution inlet temperature will increase the equilibrium water vapor pressure at the surface of liquid desiccant, and reduce the dehumidification rate, which consequently elevate the humidity of outlet air. By comparing the simulation results with and without this regulation strategy, it can be known that this strategy successfully avoids the concentration decreasing with self-adaptive valve opening regulation, and the increasing of outlet air humidity attributes to the growth of solution inlet temperature. This indicates adjusting the inlet solution temperature is an applicable choice in regulating the outlet air humidity.

Figure 4.22 Concentration regulations without disturbances (Case 1)

To adjust the solution temperature accordingly can expand the acceptable working range of working solution concentration, and a supplement analysis is performed to verify the feasibility of the performance of the proposed strategy with the criterion as Eq. (4-13b). The concentration set point is changed from 26.3% to 27.4%, concurrent with a step input of inlet solution temperature raises from 16.5 °C to 17.2 °C at the 120 min. According to the illustrations in Figure 4.23, a long valve opening occurs attributing to the increase of working solution concentration at the 120 min. Along with the strong solution supplied into the working solution tank, the liquid level in the buffer decreases, and eventually, the flow rate of strong solution decreases. In each cycle of calculation, the valve opening duration is determined by the strong solution level in the buffer on the spot. A larger deviation between the present value and the set point results longer value opening. During this valve-opening period, the supplied rate of the concentrated solution decreases with the solution amount in the buffer, and provided less strong solution than expected. To prevent this phenomenon, a new round of calculation is triggered immediately, which can be

observed from the first picture of Figure 4.23 at around 126min. The working concentration remains at the new set point around 27.4%, and indicates that regulating the solution temperature of 0.7°C extends 1.1% of the acceptable working concentration without affecting the outlet air humidity in the present operating conditions.

Case 3: Simulation with step change of inlet air humidity

The inlet air humidity ratio plays an important role in humidity regulations, especially when LDDS is applied to remove the moisture of the fresh air directly. In this kind of situations, the dehumidification rate should be manipulated according to the outdoor air conditions to handle the unnecessary variations of the latent loads. Therefore, the performances with unstable inlet humidity conditions are important in validating this strategy thoroughly.

Four groups of simulations are carried out in this case. Among these four groups, three are conducted in the same environments, i.e. inlet air humidity ratio is increased at the 120min from 12.0 g/kg dry air to 15.0 g/kg dry air. The differences among these groups lie in the regulation strategies. One regulates the working concentration at 26.3%, and another one controls the concentration at 28.4% to keep the outlet air humidity stable. The last one is conducted without concentration regulation. These three groups are denoted as Regulatedload+, Regulatedd+ and Non-Regulated, respectively. The group of simulation conducting with a decreased of outlet air humidity from 12.0 g/kg dry air to 10.0 g/kg dry air is denoted as Regulatedload- as shown in Figure 4.24.

As illustrated in Figure 4.24, the valve opening duration and frequency are increased to balance the increasing latent load. Similarly, the valve opening duration and frequency decrease when the latent load decreases. Again, in the environment with disturbances, this controller manages to maintain the working solution concentration at the required set point 26.3% or 28.4% with disturbances. In the condition of Regulatedd+, the buffer reaches the lowest liquid level at 145.2min and requires for supplement of strong solution. From Figure 4.24, it can be observed that the change of working solution concentration needs about 12 mins to take effect, and nearly 10 more mins to regain the stable of the outlet air humidity.

Figure 4. 23 Concentration regulations with varied solution temperature (Case 2)

Figure 4. 24 Concentration regulations with varied inlet air humidity (Case 3)

4.6 Implementation results of the regulation strategy

Both strong solution buffer and the working solution tank have a volume of 0.4 m^3 . The diameter, vertical height, and total length of the connecting tube between the two tanks are 0.025m, 0.15m and 0.4 m, respectively. Specific to the structure of this dehumidifier, the coefficient of local resistance for two ninety-degree bends are $\zeta_{turn1} = 0.66$ and $\zeta_{turn2} = 0.66$. ζ_{valve} is zero when the ball valve is fully opened [123] and the dynamic viscosity of desiccant solution is 3×10^{-3} [44]. The flow rate of strong solution is calculated by Eq. (4-11) and verified by the volume increments in the working solution tank. The MRE and RMSRE are 7.26% and 0.0819, respectively.

Experiments are carried out in a room with stable air conditions. The air temperature is 22°C and humidity ratio is 11.8 g/kg dry air. The air supplied to the dehumidifier has a controlled velocity of 1.0 m/s during the whole operating period, and the target working concentration is 26.5% with $\pm 1\%$ acceptable error. The desiccant mass flow rate is kept at constant values of 17.5L/min and inlet solution is manipulated to stabilize the outlet air humidity at around 15°C . A four-hour experiment is conducted to validate the efficiency of this concentration regulation strategy as revealed in Figure 4.25. With this regulation strategy, the outlet air humidity is successfully maintained at 6.5 g/kg dry air. The start time for solution transfer is noted with a circle, and this process occurs when the working solution exceeds the capacity of working solution tank. The charge time of strong solution is regulated and illustrated as line segments in Figure 4.25. The outlet air humidity is kept at around 6.5 g/kg dry air and the concentration decreasing is totally removed in this 240 mins. The energy consumed by solution transfer reduced up to 90% compared with continuously solution transfer strategy, which would be a large amount of energy when the components of the system have certain distances with each other. Since the working concentration influences the efficiency of heating and cooling source, to govern the working concentration wisely will increase the energy efficiency of LDDS significantly.

Figure 4. 25 Concentration regulation experiments (240min)

4.7 Summary

This Chapter focused on the issues associated with the concentration of liquid desiccant in the LDDS. To measure the working solution concentration of each side, soft-sensors with different input variable numbers and fuzzy rule numbers were developed, validated, and compared. The most appropriated structure of the soft-sensor was discussed in the regeneration side, and then directly applied in the dehumidification side. Parameters of the soft-sensor were well tuned and experiments have been conducted to validate the soft-sensor accuracy in different working conditions. According to the validation results, the predicted concentrations were consistent with the experimental values. By comparing the soft-sensing accuracy and structural complexity, the model-based optimized ANFIS had a most concise structure with a good accuracy ($\text{RMSE} < 0.02$).

To keep the working solution concentration constant in the dehumidifier, the strong solution in the solution buffer has been controlled to supply to the working solution tank by a regulating valve. A control strategy has been explained in this chapter, and simulations were carried out to determine the criteria necessary for the concentration regulation. By regulating the solution concentration inside the dehumidifier into an appropriate range, the dehumidifier was able to provide stable outlet air humidity. In the simulations with and without disturbances, the valve opening time length and frequency were adjusted adaptively with environmental disturbances or solution conditions inside the dehumidifier to maintain the working solution concentration. This strategy not only revealed its effectiveness in the working solution concentration regulation, but also showed the potential of control the

outlet humidity with a regulated working solution concentration in the dehumidifier. Experimental studies on an actual operating LDDS showed the effectiveness of this strategy.

Chapter 5. Optimization of the Working Solution Concentration

5.1 Introduction

Though Chapter 4 solves the issues of the measurement and regulation of the solution concentration, more topics needed to be concerned to fulfill the distributed operating scheme. Selecting a proper working solution concentration pairs for dehumidifier and regenerator is one of these tasks. In the distributed operating scheme, the working solution concentration of dehumidifier should be determined respect to the operating status and the occupants' requirements. The regenerator requires a target concentration to stop the regeneration, and the strong solution with fixed concentration will be supplied to all the strong solution buffers. The applicable termination concentrations for regenerator are more than one. Moreover, in the dehumidifier, different combinations of working solution concentration and solution temperature can achieve the same outlet air humidity. Therefore, to find out the optimal combinations among those feasible choices, a criterion should be select to obtain the working solution concentrations in different components.

Since LDDS is an energy intensive system [124, 125], many efforts have been paid to improve its energy efficiency. Ham et al.[126] developed a 100% outdoor air system assisted by liquid desiccant, and this system could provide the treated air to the conditioned space utilizing 100% outdoor air with satisfied energy consumption from the simulation results. Qi et al. [127] deliberated the operation performance of the internally cooled/heated dehumidifier/regenerator and optimized the energy performances in different operating conditions. Wang et al. [128, 129] used genetic algorithm and self-adapt evolutionary algorithm to optimize the energy consumption of dehumidification side and the overall liquid desiccant dehumidification system. The experimental results showed that the proposed optimization strategy can save 12.2% of the energy consumption in dehumidification side and 18.5% in the integrated system.

Though energy problems have been widely deliberated, very little attention has been paid to explore the associations between desiccant concentration and energy consumptions. Among the few investigations associated with desiccant concentrations, Chen et al. [130] suggested a mass concentration range between

25.4–26.9% can optimize system coefficient of performance at temperature and low concentration. She et al. [131] explicated the most appropriate concentration through the performance analysis of the condensation heat driven system proposed in their works. Generally, high desiccant concentration in the dehumidifier requires less cooling energy to chill down the desiccant solution to derive the same dehumidification effect. In the meantime, high desiccant concentration in regenerator increases the difficulty of moisture migrating from the diluted solution to regenerator air [68] and the regeneration temperature should be raised to overcome this resistance. Higher temperature requires more energy. Therefore, the concentration of desiccant solution is a variable extremely correlated to the energy consumption of LDDS.

This Chapter focuses on selecting the optimal working solution concentration pairs of LDDS from the view of energy conservation. By utilizing the physical and energy models explicated in Chapter 5.2, the component and overall energy consumption of LDDS have been evaluated in Chapter 5.3. Genetic algorithm is adopted to figure out the most energy saving concentrations in dehumidifier and regenerator with the constraints of physical, operational and pre-specified outlet air requirements as explained in Chapter 5.4. The parameters of the mentioned models are explained in Chapter 5.5 and the optimization results are reported in Chapter 5.6, with a short summary in the last session of this chapter.

5.2 Component model development

5.2.1 Heat exchanger model

A simplified heat exchanger model is applied here to evaluate the solution inlet temperature of the dehumidifier and regenerator. The heat transfer between the two working fluids, desiccant solution and water, occurs in the heat-exchanger as depicted in Figure 5.1.

Figure 5. 1 Diagram of heat exchanger

The effectiveness of a counter-flow heat exchanger is [132]:

$$\varepsilon = \frac{1 - \exp\left\{(-NTU) \left[1 - \frac{(\dot{m}c)_{\min}}{(\dot{m}c)_{\max}}\right]\right\}}{1 - \frac{(\dot{m}c)_{\min}}{(\dot{m}c)_{\max}} \exp\left\{(-NTU) \left[1 - \frac{(\dot{m}c)_{\min}}{(\dot{m}c)_{\max}}\right]\right\}} \quad (5-1)$$

where $(\dot{m}c)_{\max}$ and $(\dot{m}c)_{\min}$ are the maximum and minimum values of the product of mass flow rate and the specific heat of two fluids, respectively. NTU is the Number of Transfer Units which can be calculated with $NTU = \frac{kA}{(\dot{m}c)_{\min}}$ as explained in [132], of which k is the overall heat transfer coefficient and A is the heat transfer area.

The heat transfer rate can be expressed as:

$$\dot{Q} = \varepsilon (\dot{m}c)_{\min} (T_{s,in,hex} - T_{w,in,hex}) \quad (5-2)$$

of which $T_{s,in,hex}$, $T_{w,in,hex}$ are the solution and chilled water temperature at the inlet of the heat exchanger.

The outlet solution temperature of heat exchanger, also the solution inlet temperature for dehumidifier can be calculated by combining Eq. (5-1) and Eq. (5-2) as:

$$T_{s,out,hex} = T_{s,in,hex} - \varepsilon \frac{(\dot{m}c)_{\min}}{c_s \dot{m}_s} (T_{s,in,hex} - T_{w,in,hex}) \quad (5-3)$$

5.2.2 Mass transfer model

Simplified mass transfer models proposed in [69, 78, 129] have been implemented to describe the moisture exchanging between the two working fluids. The prediction of outlet air conditions relies on the model explained in Eq.(5-4), which is a function of the solution mass flow rate, inlet air and solution temperature, inlet air humidity and desiccant concentration.

$$N_{D/R} = \frac{\hat{c}_{1,D/R} (\dot{m}_{s,D/R})^{\hat{c}_{3,D/R}}}{1 + \hat{c}_{2,D/R} T_{a,in,D/R} (\dot{m}_{s,D/R})^{\hat{c}_{3,D/R}} (\dot{m}_{a,D/R})^{\hat{c}_{4,D/R}}} \left| P_{a,in,D/R} - P_{s,in,D/R}^* (c_{s,D/R}, T_{s,in,D/R}) \right| \quad (5-4)$$

5.2.3 Energy models of pump and fan

The power input of pump and fan can be conducted as:

$$P_p = P_{p,nom} \left(a_{p,3} \left(\frac{\dot{m}_s}{\dot{m}_{s,nom}} \right)^3 + a_{p,2} \left(\frac{\dot{m}_s}{\dot{m}_{s,nom}} \right)^2 + a_{p,1} \left(\frac{\dot{m}_s}{\dot{m}_{s,nom}} \right) + a_{p,0} \right) \quad (5-5a)$$

$$P_f = P_{f,nom} \left(a_{f,3} \left(\frac{\dot{m}_a}{\dot{m}_{a,nom}} \right)^3 + a_{f,2} \left(\frac{\dot{m}_a}{\dot{m}_{a,nom}} \right)^2 + a_{f,1} \left(\frac{\dot{m}_a}{\dot{m}_{a,nom}} \right) + a_{f,0} \right) \quad (5-5b)$$

where P_p , P_f , $P_{p,nom}$, $P_{f,nom}$, $\dot{m}_a$, $\dot{m}_s$, $\dot{m}_{a,nom}$, $\dot{m}_{s,nom}$ are the current power consumption of pump and fan, nominal power consumption of pump and fan, current air and solution mass flow rate, nominal air and the mass flow rate of desiccant solution, respectively, $a_{p,0} - a_{p,3}$, $a_{f,0} - a_{f,3}$ are the parameters to be determined for the energy models.

5.2.4 Heat source model

The heat source provides heat to the regenerator, and has the potential to apply industrial waste heat or solar energy. With appropriate simplification and generalization, a generalized model of heat source can be presented by Eq.(5-6).

$$E_{sths} = \frac{c_s m_s (T_{s,in} - T_{s,out})}{\eta} - E_{lowG} + E_{hssus} \quad (5-6)$$

where m_s is the mass flow rate of desiccant solution in regenerator, $T_{s,in}$ and $T_{s,out}$ are the desiccant solution temperatures of at the inlet and outlet of the heat exchanger, E_{lowG} is the energy provided by low grade heat, E_{hssus} is the energy consumed by the heat source system.

The Eq. (5-6) can be utilized to describe different kinds of heat sources such as electrical heater and solar energy heater. If Eq. (5-6) is used for a common electrical heater, the low grade heat term E_{lowG} should be zero, and E_{hssus} is the energy consumed by the pump when pumps up the hot water to provide heat to desiccant solution. Solar energy system, generally utilizing water as the energy storage medium, can also be described with Eq. (5-6). The low grade heat term E_{lowG} is the energy provided by solar energy, and the heat source sustained term E_{hssus} consists of the energy consumed for the solar energy system and hot water circulation.

5.2.5 Cooling source model

The cooling sources that can be used by LDDS are building chilled water, heat pump evaporator and other complicated sources, the efficiency cannot be derived with a unified equation due to the diversity of the cooling processes. A generalized analysis is to calculate this part of energy from the chilled water side, as described as Eq. (5-7).

$$E_{stcs} = c_{cw} m_{cw} (T_{cw,in} - T_{cw,out}) + E_{cssus} \quad (5-7)$$

where $T_{cw,in}$ and $T_{cw,out}$ are the inlet and outlet chilled water temperature, c_{cw} and m_{cw} are the specific heat and mass flow rate of chilled water. E_{cssus} is the energy used for circulating the chilled water to cool down the temperature of the desiccant solution.

5.2.6 Solution transfer model

The energy cost in solution transfer can be roughly estimated by the product of the transferring time duration and the power of energy consumed by the transfer facilities. The mass of solution transfer among the components can be calculated with Eq. (5-8a), and the energy consumed by solution transfer depends on the system scale and distribution of system components, as expressed in Eq.(5-8b).

$$M_T = \sum_{i=1}^M \dot{m}_{Ti} t_T \quad (5-8a)$$

$$E_T = \sum_{i=1}^M P_{Ti} t_T \quad (5-8b)$$

where t_T transferring time duration. The mass transfer rate $\dot{m}_T$ and power of each transfer pump P_T can be decided in the stage of system design and installation.

5.3 Energy consumption of the system

An intermittent operating strategy has been introduced in this study, and the solution transfer only occurs when the working solution concentration of dehumidifier is insufficient. It should be noted that the mass transfer rate of regeneration process is higher than the rate of dehumidification, and is practical

to utilize this intermittent strategy.

The total energy consumption of an LDDS system can be expressed as Eq. (5-9):

$$E = E_T + E_R + E_{sths} + \sum_{i=1}^N (E_D + E_{stcs})_i \quad (5-9)$$

where $E_T, E_R, E_{sths}, E_D, E_{stcs}$ are the energy consumption of solution transfer, regenerator, heating source, dehumidifier, and cooling source, respectively. N is the number of dehumidification units in the distributed system.

The solution transfer energy E_T is the energy utilized to circulate the desiccant concentration among regenerator, dehumidifier and solution storage tanks, which can be calculated with Eq.(5-8b).

The desiccant solution gradually loses the affiliation to the moisture during the system operating, and a new round of solution transfer will be triggered when the dehumidification rate cannot meet the requirement. The time length of each cycle can be calculated with Eq.(5-10) based on mass conservation principle.

$$t_d = \frac{\rho_{str} V_{str} c_{str} - c_{dilu} \rho_{dilu} V_{dilu}}{c_{dilu} \dot{m}_D (c_{dilu}, T_{s,in})} \quad (5-10)$$

where $\rho_{str}, \rho_{dilu}, V_{str}, V_{dilu}, c_{str}, c_{dilu}$ are the density, volume and concentration of the strong and weak solution, respectively, $\dot{m}_D$ is the mass transfer rate of the moisture transferred from the air to the desiccant solution.

The number of solution transfer occurs in a running period $t_{overall}$ can be

round up to an integer as:
$$N_t = \left\lceil \frac{t_{overall} c_{dilu} \dot{m}_D (c_{dilu}, T_{s,in})}{(\rho_{str} V_{str} c_{str} - c_{dilu} \rho_{dilu} V_{dilu})} \right\rceil.$$

The regenerator energy consumption E_R is the energy cost by fan and pump when the regenerator is in the operating status.

The regenerator will stop working when the solution concentration reaches c_{str} and waiting for the next round of regeneration launched by dehumidifier. In a multi-dehumidifier system, the regeneration concentration set point c_{str} must be able to meet the requirement of all the dehumidification terminals as described in Eq. (5-11):

$$c_{str} = \max(c_{dilu1}, c_{dilu2} \dots c_{diluN}) + c_0 \quad (5-11)$$

where c_{dilu} is the target operating concentration for dehumidifier unit i , and c_0 is the necessary concentration differences between the strong and weak solution.

The energy consumed by the regenerator is expressed as Eq. (5-12).

$$E_R = (P_p + P_f) \cdot N_t \cdot t_r \quad (5-12)$$

where t_r is the time length a regeneration period needs, which can be calculated with Eq. (5-13). The summary of P_p and P_f denotes the power of regenerator fan and pump expressed by Eq. (5-5a) and (5-5b). The energy cost by regenerator is expressed as the product between power consumption and the operating time.

$$t_r = \frac{(\rho_{dilu} V_{dilu} c_{str} - c_{dilu} \rho_{dilu} V_{dilu})}{c_{str} \dot{m}_R (c_{dilu}, T_{s,in})} \quad (5-13)$$

Term $\dot{m}_R$ represents the mass transfer rate from the solution to the process air inside the regenerator. The Eq. (5-13) explains the time consumed by the regenerator to regenerate the strong concentration to c_{str} from the weak concentration c_{dilu} .

Variety types of heat sources can be implemented to provide the driving force for regenerators, such as solar energy, heat pump condenser, water heater and industrial waste heat. This part of energy, which is noted as E_{sths} , can be calculated with Eq. (5-6).

The term E_D expresses the energy consumed by a dehumidifier terminal. In this study, the dehumidifiers are running continuously to absorb the moisture of the process air, and the energy consumption is the energy costs by fan and pump in the time range $t_{overall}$:

$$E_D = (P_p + P_f) t_{overall} \quad (5-14)$$

The cooling amount provides to the system by cooling sources E_{stcs} is calculated from the heat exchanger model with Eq. (5-7).

5.4 Concentration optimization

The goal of the optimization is to search the concentration pairs of strong and

weak solution to minimize the total energy consumption of LDDS, and this section explains the optimization strategy including the objective function and the constraints.

5.4.1 Objective function

The objective function of this optimization strategy is expressed as Eq. (5-9), which involves the energy consumptions of solution transfer, regenerator, heating source, dehumidifier and the cooling source. Distinct from most of the optimizations in LDDS fields, the optimization strategy here regards the weak and strong concentrations c_{dilu} and c_{str} as control variables, together with the commonly applied control variables, desiccant mass flow rate and chilled water flow rate. The desiccant mass flow rate is regulated by the pump frequency, and the chilled water mass flow rate is controlled by a regulating valve on the chilled water pipe. The strong and weak concentrations are regulated by concentration controllers with the strategy explained in Chapter 3 and 4.

5.4.2 Constrains

Some constraints are imposed to ensure the physical feasibility during the system operation. Physical constraints, operational constraints, and outlet humidity requirements are all considered during the optimization to find the energy optimal concentration pairs.

The mass flow rate desiccant solution and chilled water must within the boundaries:

$$\dot{m}_{s,min} \leq \dot{m}_s \leq \dot{m}_{s,max} \quad (5-15a)$$

$$\dot{m}_{cw,min} \leq \dot{m}_{cw} \leq \dot{m}_{cw,max} \quad (5-15b)$$

where $\dot{m}_{s,min}$, $\dot{m}_{s,max}$, $\dot{m}_{cw,min}$ and $\dot{m}_{cw,max}$ are the lower and upper boundaries of the mass flow rate of liquid desiccant solution and chilled water, respectively. The values outside these ranges might not be reached due to the system limitations or unsafe for continuously operation.

Some operational constraints should be satisfied to realize the intermittent operating strategy, as the following inequalities:

$$N_D \leq N_R \quad (5-16a)$$

$$T_R + T_T < T_D \quad (5-16b)$$

The dehumidification rate N_D should be lower than regeneration rate N_R , and should be considered in the stage of system design. This can be easily achieved since regenerator usually has an observable higher mass transfer rate than dehumidifier. The time consumed by regenerator T_R and solution transfer T_T need to be shorter than the time length cost by the dehumidification T_D in a single round of solution transfer to ensure the continuous operation of the whole system.

To realize the independent control of humidity, the outlet air humidity ratio is constrained to meet the requirements of the occupants as:

$$\left| HR_{a,out,D} - RH_{a,out,sp,D} \right| \leq \varepsilon$$

where $HR_{a,out,D}$ and $RH_{a,out,sp,D}$ are the current and required outlet air humidity ratio.

The variables $T_{a,in,D\&R}$ and $RH_{a,in,D\&R}$ depends on the supply air condition, and $\dot{m}_{a,D\&R}$, $T_{a,out,sp,D}$ and $RH_{a,out,sp,D}$ are determined by the requirements of the design. The chilled water temperature $T_{cw,in}$ is regulated to be stable. These above mentioned variables are assumed to be constants during the optimization procedure.

5.4.3 Optimization Strategy

A model-based optimal strategy with structure described in Figure 5.2 is utilized to calculate the appropriated input combinations. Each component has a physical model and a corresponding energy model, and different dehumidifiers may have particular set points and cooling sources. Genetic algorithm [113, 133] is employed to minimize the energy fitness function value, Eq.(5-9), under the constraints of physical, operating and the requirements of occupants.

The chromosomes of genetic algorithm contain four genetic series encoding with binary-code decimal rules, and the physical meanings are working solution in dehumidifier, mass flow rate of chilled water, mass flow rate of desiccant solution and target strong solution in regenerator in order.

Figure 5.2 Scheme of the optimization strategy

Ninety percent of the initial population is generated randomly, while the other 10% are the chromosomes appear with a high frequency from the experimental results. The randomly generated chromosomes are ranked based on the values of objective functions calculated from Eq. (5-9) utilizing the top-ranking method with a 40% acceptable threshold. Those unsatisfied chromosomes will be weakened or eliminated during the offspring generating, and the new generation will be created. The parent chromosomes generate the offspring in the next generation by selection, crossover and mutation until the optimal chromosome is found. The GA terminates when the maximum number of generations is reached or the average relative change between two generations is below the tolerance. The flowchart of the optimization strategy is shown in Fig.5.3.

Figure 5. 3 Scheme of the optimization strategy

5.5 Model parameters

The constraints of uncontrollable and controllable variables are demonstrated in Table 5.1, and the nominal capacities and other parameters in energy models are listed in Table 5.2.

Table 5. 1 Variable operating range

Variable Name	Maximal operational Value	Minimal operational value
$T_{a,in,D\&R}$ (°C)	25	20
$RH_{a,in,D\&R}$ (g/kg dry air)	18	11
$\dot{m}_{a,D\&R}$ (kg/s)	0.128	0.288
$\dot{m}_s$ (kg/s)	0.20	0.60
$\dot{m}_{cw}$ (kg/s)	0.20	0.60
c_{aim} (%)	21	30
c_s (%)	31	40

Table 5. 2 Energy parameters

Variable	P_T (kw)	P_P (kw)	P_F (kw)	P_{CW} (kw)	P_{HW} (kw)
Value	0.375	0.375	0.385	0.375	0.375

The energy consumptions of the cooling and heating source, pumps and fans can be calculated with the fitting equations from the experimental data. By using these models, the used energy can be predicted accurately. The

parameters of the fan and pump model are displayed in Table 5.3. The unknown parameters of mass transfer models are calculated with Levenberg–Marquardt method [134], and the data are collected from the experiments with different environmental conditions. The parameters of mass transfer coefficients are the same as the physical model of the soft-sensors presented in Chapter 4, and those parameters have been listed clearly in Table 5.4.

Table 5.3 Energy model parameters

Pump	$a_{p,3} = 0.4695$	$a_{p,2} = 0.1215$	$a_{p,1} = 0.5000$	$a_{p,0} = 0.1679$
Fan	$a_{f,3} = 0.1092$	$a_{f,2} = 0.7296$	$a_{f,1} = 0.5000$	$a_{f,0} = 0.0304$

Table 5.4 Mass and heat transfer model parameters

Mass transfer DE	$\hat{c}_1 = 0.1249$	$\hat{c}_2 = 2.3562$	$\hat{c}_3 = 2.3500$	$\hat{c}_4 = 0.7949$
Mass transfer RE	$\hat{c}_1 = 0.0100$	$\hat{c}_2 = 8.0010$	$\hat{c}_3 = 5.0290$	$\hat{c}_4 = 4.9830$

5.6 Optimization results and discussions

A series of analysis has been carried out to discuss the system performance with different strong and weak solution concentrations and solution/chilled water mass flow rate pairs. In the 15-hour simulation, the outlet air humidity is regulated at 7.5g/kg dry air, and a ± 0.05 g/kg dry air error is acceptable. The best fit chromosome from the optimized algorithm is 0.257 0.201 0.401 0.301 with the genetic sequences explained in Chapter 5.4.3. Comparisons have been carried out to analyze the impact of the concentration on the energy consumption and prove the efficiency of this optimization method in finding an energy optimal working solution pair.

5.6.1 Energy consumption with varied weak solution concentrations

To analyze the impact of weak solution concentration on the energy consumptions of LDDS, a series of discussions have been carried out within a concentration ranging from 20% to 29.5%. The tendency of energy consumptions vs. weak solution concentrations are illustrated in the Figure 5.4-Figure 5.9. The values in the rectangle boxes are those conditions satisfied the required outlet air humidity with an accuracy of ± 0.05 g/kg dry air. The

chilled water flow rates are 0.60 kg/s, 0.40kg/s and 0.20 kg/s at the corresponding working solution concentration marked in the x-axis.

As can be observed in Figure 5.4, stable running status of pump, fan, and chilled water valves leads to the steady energy consumptions of dehumidifier and cooling source. Figure 5.4 and 5.5 reveal the associations between the concentrations of working solution and energy consumptions of cooling source and dehumidifier when other variables are kept as constants. Higher working solution concentration reduces the requirement of the cooling energy, and cuts down the energy consumption of cooling source. Since the mass flow rate of dehumidifier and chilled water remain constant in this discussion, no energy differences can be observed from Figure 5.4 and Figure 5.5.

Low working solution concentrations require low chilled water temperatures to achieve the same dehumidification outcomes, and this eventually increases the usage of cooling energy. Raising the working solution concentration is a method to reduce the load of the cooling source. However, raising this concentration narrows the gaps between the strong and weak solutions, and increasing the operating time length of the regenerator and heat sources. This turns out to have an increase of the energy consumption of regeneration side as described in Figure 5.6 and Figure 5.7. The energy consumption grows significantly as the concentration of working solution in the dehumidifier approaches to 30%, at the condition when the target concentration of regeneration (denoted as c_s in Figure 5.6 and Figure 5.7) is 30%. The increasing of regeneration time length and solution transfer times cause this phenomenon as the concentration gaps between the two working solutions reduced.

Figure 5. 4 Cooling source vs. weak solution

Figure 5. 5 Dehumidifier vs. weak solution

As can be observed in Figure 5.8, high working solution concentration of dehumidifier increases the number of times of solution transfer, and increases the energy consumed by solution transfer. One regenerator vs one dehumidifier scheme is used here with two transfer pumps at the power of 0.375kw. The energy consumed by solution transfer increases with the scale of LDDS. If the scale of LDDS enlarges to a building level with multiple terminals, the weights of transfer energy will increase to a significant amount.

Figure 5. 6 Heat source vs. weak solution

Figure 5. 7 Regenerator vs. weak solution

The overall energy consumption is roughly proportional to the working solution concentration of dehumidifier as illustrated in Figure 5.9. High working solution concentration of dehumidifier reduces the energy consumption of dehumidification but increases the energy cost considerably to overcome the resistance of regeneration at a high concentration. If part of the heat for regeneration can be provided by renewable or waste heat, the energy consumption will reduce as disclosed in Figure 5.10 and Figure 5.11.

The Figure 5.4 - Figure 5.9 demonstrates that operating the system at the optimal desiccant concentration can reduce the energy consumption of the regenerator and heat source, and increases the energy usage for solution transfer

at the same time. If a percentage of this heat can be provided by renewable energy, high working solution concentration of dehumidifier will also be an attractive choice in energy saving with proper working pairs of control variables.

Figure 5. 8 Solution transfer vs. weak solution

Figure 5. 9 Overall energy vs. weak solution

Figure 5. 10 Comparisons of overall energy

Figure 5. 11 Comparisons of heat source

5.6.2 Energy consumption with varied strong solution concentrations

As described in Figure 5.12 and Figure 5.13, the chilled water flow rate at 0.20 kg/s, 0.20kg/s and 0.60 kg/s with corresponding working solution concentration at 25.5%, 24% and 25% can achieve the required outlet humidity with errors marked in the figures. The cooling source delivers more energy to the dehumidifier when the flow rate of desiccant solution and chilled water grows larger, and the dehumidifier energy consumption is positive related to the desiccant mass flow rate, which can be clearly observed from Figure 5.12 and Figure 5.13. The energy consumed by dehumidifier is related to the operating

condition of its circulation pump and fan. The working status of the fan controls the amount of supply air, which does not have too much space to improve due to the requirements, but the mass flow rate of desiccant solution is adjustable through the working frequency of the pump. A varied flow rate of desiccant solution, chilled water and different concentration pairs are introduced in this case to analyze the system performance. Due to the concentration regulation strategy explained in Chapter 4, the dehumidification side will not be influenced by different strong solution concentrations. The impacts of other three variables can be observed in Figure 5.12- Figure 5.17.

Figure 5. 12 Cooling source vs strong solution

Figure 5. 13 Dehumidifier vs strong solution

Figure 5. 14 Heat Source vs strong solution

As depicted in Figure 5.14 and Figure 5.15, to achieve the required outlet humidity ratio, different combinations of flow rate of the chilled water and desiccant solution and working concentration can be applied. The analysis of this group again strengthens the necessity of finding a most energy efficiency input variable pairs among those feasible choices with complicate requirements and constraints. Figure 5.16 displays the energy consumed by solution transfer has an inverse relation with the target concentration of the strong solution. The performance of the cooling side highly affects the overall energy consumption as illustrated in Figure 5.17. Though the combinations of input variables are different, condition 2 and 3 consume almost the same energy.

Comparisons have been carried out to study the energy consumptions of LDDS under continuously and intermittent solution transfer methods and the results are demonstrated in Figure 5.18. The analysis only covers the energy consumption of regeneration side, since the dehumidification side is always operating continuously. This intermittent operation method reduces at most 40% in the energy consumption of the regeneration side. A point need to mention here is the intermittent operating scheme may be totally removed if a proper number of dehumidifiers have been chosen.

Figure 5. 15 Regenerator vs strong solution

Figure 5. 16 Transfer vs strong solution

Figure 5.17 Overall vs strong solution

Figure 5.18 Comparisons between continuous and intermit operations

5.7 Summary

This Chapter presented the relations between desiccant concentrations and energy consumptions of LDDS, and suggested the most energy efficiency concentration pairs among those applicable combinations.

The energy usages of components and processes under different operating concentrations have been calculated with experimental validated models. Genetic algorithm was employed to select the optimal combination of weak and strong desiccant concentration, solution mass flow rate of the dehumidification side and chilled water mass flow rate. The component and overall energy consumption at the optimal operating concentration were discussed and compared. The results illustrated that the appropriated operating concentrations in dehumidifiers and regenerator can redistribute the energy consumption among the components and realize the energy saving. To reach the same outlet humidity conditions, operating the system at the optimal concentration reduces around 23% of the overall energy consumption, and different operating scheme or energy supply methods properly results different optimal values based on the analysis results.

Chapter 6. Humidity Control of the Dehumidifier

6.1 Introduction

In both of the design and optimization of LDDS, a stable humidity level of supply air always comes first. Appropriated indoor air humidity improves the occupants' thermal comfort, avoids the body distress and some disorders of the respiratory system, and also provides a drier environment for the storage of food, chemical materials and industrial instruments.

To achieve certain outlet air humidity ratio, the concentration of liquid desiccant must be regulated inside a specific range, and otherwise the humidity ratio set point cannot be reached. Additionally, the concentration needs to be regulated to maintain the working concentration in multiple dehumidifiers with the batch operation mode. This control issues have been elucidated in Chapter 4. However, it is not sufficient to rely on concentration regulation only since the LDDS responses faster on other variables, such as the inlet solution temperature. The concentration regulation is indispensable because regulating other variables becomes ineffective when the liquid desiccant concentration is out of a certain range. But relying on the liquid desiccant concentration alone is not sufficient to handle the disturbances with fast response and also wastes the mature technologies in measuring and controlling the solution temperature during the system operation.

This chapter introduces a method to regulate the solution inlet temperature to fine tune the outlet air humidity within a regulated solution concentration range. Some literature reviews on the control issues of dehumidification systems are clarified in Chapter 2.5. Concluded from the previous research works, Fuzzy-PID is one of the applicable choices to regulate the outlet humidity by manipulating the solution inlet temperature. This Chapter firstly explains a methodology in manipulating the solution inlet temperature to regulate the outlet air humidity, and then combines other modules described in previous chapters to investigate the overall performance of this strategy. The working solution concentration inside dehumidifier is maintained in a range controlled by the strategy explained in Chapter 4. A mapping generated from Chapter 5 serves as a dataset to determine the appropriated working solution concentration, and the outlet humidity is regulated by a Fuzzy-PID controller.

The control diagram is shown as Figure 6.1. The plant model of LDDS is introduced in Chapter 3, and the concentration regulator and soft-sensors are elaborated in Chapter 4. The concentration optimizer maps the relations between humidity and working solution concentration was generated from Chapter 5. Firstly, Chapter 6.1 and 6.2 focuses on the red rectangle part of Figure 6.1. Then, the simulations and comparisons of the combinations of all the modules explained in this thesis are carried out in Chapter 6.3, and the experimental validations are analyzed in Chapter 6.4. Finally, the summary of this chapter is given out in Chapter 6.5.

Figure 6. 1 Overall control diagram

6.2 Controller design

A cascade control structure has been applied to control the outlet air humidity. A primary controller generates the inlet solution temperature serving as the set point of the secondary controller. The secondary controller manipulated the flow rate of the chilled water to provide desiccant solution with a fixed temperature. Cascade control framework is feasible due to the secondary loop has a significant faster dynamic response than that of the primary loop. There are two reasons to use a cascade structure, one is to reduce or eliminate the inner loop disturbance affected by the heat transfer between the liquid desiccant and the chilled water or refrigerate, and the other is to better analyze the impact of solution inlet temperature on the dehumidification.

6.2.1 General PID controller

In practice, the process models are usually represented by low order plus dead-time models. The inlet solution temperature is regulated though the chilled water flow rate, which is appropriated with a first order plus time delay as

Eq.(6-1a) estimated from original experimental data. The LDDS plant is simplified as a second order plus dead time in the process of controller design with the forms of Eq.(6-1b).

$$G_{p_1}(s) = \frac{k}{T_S + 1} e^{-Ls} \quad (6-1a)$$

$$G_{p_2}(s) = \frac{b_0}{a_2 s^2 + a_1 s + 1} e^{-Ls} \quad (6-1b)$$

The parameters of secondary controller are tuned with a P structure controller as Eq.(6-1b), steady state errors are acceptable for the tuning of secondary controller. The primary PID control employed a PID structure as Eq.(6-2b):

$$G_{sc}(s) = K_{psc} \quad (6-2a)$$

$$G_{pc}(s) = K_p + \frac{K_I}{s} + K_D s \quad (6-2b)$$

The parameters are determined using the gain and phase margin method [135] as following:

$$K_p = \frac{\pi a_1}{2 A_m L b_0} \quad (6-3a)$$

$$K_i = \frac{\pi}{2 A_m L b_0} \quad (6-3b)$$

$$K_d = \frac{\pi a_2}{2 A_m L b_0} \quad (6-3c)$$

6.2.2 Fuzzy-PID controller

The fuzzy-PID controller is designed with a T-S fuzzy model including the system responses at current and previous timestamps. The original mathematical model with 5 layers explained in Chapter 3 can be written with a form:

$$\begin{aligned} \dot{\mathbf{X}}(t) &= \mathbf{f}(t, \mathbf{X}(t), \mathbf{U}(t)) \\ \mathbf{Y}(t) &= \mathbf{h}(t, \mathbf{X}(t), \mathbf{U}(t)) \end{aligned} \quad (6-4)$$

where $\mathbf{U}(t)$ is a vector of solution inlet temperature and strong solution flow rate, $\mathbf{Y}(t)$ contains the outlet air humidity and current working solution concentration in the dehumidifier. The concentration is regulated with the

method explained in Chapter 4 independently, so the system is simplified to a SISO structure.

This structure is then expressed in fuzzy “IF–THEN” rules as:

$$\begin{aligned} \text{Rule}^m : & \text{IF } \mathbf{Z}(k) \text{ is } \mathbf{C}^m \\ \text{THEN } & y^m(k) = \alpha_0^m \cdot u(k - \tau) + \alpha_1^m \cdot u(k - \tau - 1) + \cdots + \alpha_{win}^m \cdot u(k - \tau - win) \\ & + \beta_1^m \cdot y(k - 1) + \cdots + \beta_{wout}^m \cdot y(k - wout) \end{aligned} \quad (6-5)$$

where $m = 1, 2, \dots, N$, N is the number of fuzzy rules in this fuzzy system, and $\mathbf{Z}(k)$ is a vector that consist a series of input and output variables with different window lengths. In this thesis, the window length of input *win* and output *wout* are 2 and 1, respectively. $\mathbf{C}^m$ is the center vector of the m th fuzzy rule concluded from fuzzy clustering, and $y^m(k)$ represents the output of m th rule at the current timestamp k . α and β are the fuzzy coefficients, and τ' is the time delay that can be calculated with $\tau = \tau' / T$, of which T is the sampling time.

Considering all fuzzy rules, the final output $y(k)$ is:

$$y(k) = \frac{\sum_{m=1}^N \mu^m(\mathbf{Z}(k)) \cdot y^m(k)}{\sum_{m=1}^N \mu^m(\mathbf{Z}(k))} = \sum_{m=1}^N \mu^m(\mathbf{Z}(k)) \cdot y^m(k) \quad (6-6)$$

where $\mu(\mathbf{Z}(k))$ is the fuzzy membership function.

Many mythologies have been studied to obtain or optimize the fuzzy membership functions [136-138], and this study utilizes Gustafson–Kessel (G–K) clustering algorithm [139] to cluster the collected data. The fuzzy membership coefficients here are obtained as explained in [140, 141]. The antecedents are determined by the clustering centers, while least square method is adopted to identify the parameters of the consequents. The fuzzy membership function is denoted as Eq.(6-7). The derivations of the fuzzy coefficients are provided in Appendix D.

$$\mu^m(\mathbf{V}(k)) = \begin{cases} \frac{1}{\sum_{s=1}^N \frac{\bar{D}(\mathbf{V}(k), \mathbf{V}_c^m)}{\bar{D}(\mathbf{V}(k), \mathbf{V}_c^s)}}, & \text{if } \text{all } \bar{D}(\mathbf{V}(k), \mathbf{V}_c^s) \neq 0, \\ & s = 1, \dots, N \\ 0, & \text{if } \text{any } \bar{D}(\mathbf{V}(k), \mathbf{V}_c^s) = 0, \\ & s = 1, \dots, N, s \neq m \\ 1, & \text{if } \bar{D}(\mathbf{V}(k), \mathbf{V}_c^s) = 0 \end{cases} \quad (6-7)$$

where $\mathbf{V}(k) = [\mathbf{Z}(k) \quad \mathbf{Y}(k)]$, and $\bar{D}(\mathbf{V}(k), \mathbf{V}_c^m)$ ($m = 1, \dots, N$) are the adaptive distances, which has been explained in Appendix D

Assign $\mathbf{V}(k)$ to the cluster in which it has the largest fuzzy membership, and using least square algorithm to identify the linear coefficients, and the T-S fuzzy modeling is completed.

When given a new input $\mathbf{Z}(k)$, its membership $\mu^m(\mathbf{x}(k))$ in m th fuzzy rule can be calculated by:

$$\mu^m(\mathbf{Z}(k)) = \begin{cases} \frac{1}{\sum_{s=1}^N \frac{D(\mathbf{Z}(k), \mathbf{Z}_c^m)}{D(\mathbf{Z}(k), \mathbf{Z}_c^s)}}, & \text{if } \text{all } D(\mathbf{Z}(k), \mathbf{Z}_c^s) \neq 0, \\ & s = 1, \dots, N \\ 0, & \text{if } \text{any } D(\mathbf{Z}(k), \mathbf{Z}_c^s) = 0, \\ & s = 1, \dots, N, s \neq m \\ 1, & \text{if } D(\mathbf{Z}(k), \mathbf{Z}_c^m) = 0 \end{cases} \quad (6-8)$$

where $D(\mathbf{Z}(k), \mathbf{Z}_c^m) = (\mathbf{Z}(k) - \mathbf{Z}_c^m) \cdot (\mathbf{Z}(k) - \mathbf{Z}_c^m)^T$.

The output of the T-S fuzzy model can be obtained by Eq. (6-6).

Assisted by this fuzzy model, a fuzzy-PID controller is derived. The linear polynomial of m th fuzzy rule as in Eq. (6-9) can be converted to a discrete transfer function form by through Z-transform.

$$G_{TS}^m(z) = \frac{Y(z)}{U(z)} = \frac{\alpha_0^m}{1 - \beta_1^m z^{-1} - \beta_2^m z^{-2}} \cdot z^{-\tau} \quad (6-9)$$

And a standard discrete PID controller with or without a cascade structure can be explained as:

$$G_c^m(z) = K_P^m + \frac{K_I^m T}{1 - z^{-1}} + \frac{K_D^m}{T} (1 - z^{-1}) \quad (6-10)$$

where K_P^m , K_I^m and K_D^m are the gains of the PID controller. According to the

gain and phase margins based PID tuning method [98], the parameters of the controller should be chosen to satisfy the following equation.

$$G_{TS}^m(z)G_c^m(z) = \frac{K^m T}{1 - z^{-1}} z^{-\tau} \quad (6-11)$$

where $K^m = \pi / (2A_m \tau T)$, A_m is the specified gain margin, which is interrelated to phase margin Ψ_m . Substitute Eq. (6-9) and Eq. (6-10) into Eq. (6-11), we have:

$$\begin{aligned} G_{TS}^m(z)G_c^m(z) &= \frac{a_0^m \cdot z^{-\tau}}{1 - (b_1^m z^{-1} + b_2^m z^{-2})} \cdot \left(K_P^m + \frac{K_I^m T}{1 - z^{-1}} + \frac{K_D^m}{T} (1 - z^{-1}) \right) \\ &= \frac{a_0^m \cdot z^{-\tau}}{1 - b_1^m z^{-1} - b_2^m z^{-2}} \cdot \frac{(K_P^m + K_I^m T + \frac{K_D^m}{T}) - (K_P^m + \frac{2K_D^m}{T})z^{-1} + \frac{K_D^m}{T} z^{-2}}{1 - z^{-1}} \\ &= \frac{a_0^m \cdot (K_P^m + K_I^m T + K_D^m / T) \cdot z^{-\tau}}{1 - b_1^m z^{-1} - b_2^m z^{-2}} \cdot \frac{1 - \frac{K_P^m + 2K_D^m / T}{K_P^m + K_I^m T + K_D^m / T} z^{-1} + \frac{K_D^m / T}{K_P^m + K_I^m T + K_D^m / T} z^{-2}}{1 - z^{-1}} \\ &= \frac{K^m T}{1 - z^{-1}} z^{-\tau} \end{aligned} \quad (6-12)$$

Table 6. 1 Typical gain and phase margin pairs

Ψ_m	$\pi / 4$	$\pi / 3$	$3\pi / 8$	$2\pi / 5$
A_m	2	3	4	5

In order to satisfy Eq. (6-12), we get the following:

$$\begin{cases} K_P^m = \frac{K^m T}{\alpha_0^m} \cdot (\beta_1^m + 2\beta_2^m) = \frac{\pi}{2\alpha_0^m A_m \tau} \cdot (\beta_1^m + 2\beta_2^m) \\ K_I^m = \frac{K^m}{\alpha_0^m} \cdot (1 - \beta_1^m - \beta_2^m) = \frac{\pi}{2\alpha_0^m A_m \tau T} \cdot (1 - \beta_1^m - \beta_2^m) \\ K_D^m = \frac{K^m T^2}{\alpha_0^m} \cdot (-\beta_2^m) = \frac{\pi T}{2\alpha_0^m A_m \tau} \cdot (-\beta_2^m) \end{cases} \quad (6-13)$$

Submitting Eq. (6-13) into Eq. (6-10) to obtain $G_c^m(z)$ for mth fuzzy rule as

$$\begin{aligned}
G_c^m(z) &= K_p^m + \frac{K_I^m T}{1-z^{-1}} + \frac{K_D^m}{T} (1-z^{-1}) \\
&= \frac{\pi \cdot (\beta_1^m + 2\beta_2^m)}{2\alpha_0^m A_m \tau} + \frac{\pi \cdot (1 - \beta_1^m - \beta_2^m)}{2\alpha_0^m A_m \tau} \cdot \frac{1}{1-z^{-1}} + \frac{\pi \cdot (-\beta_2^m)}{2\alpha_0^m A_m \tau} \cdot (1-z^{-1}) \quad (6-14) \\
&= \frac{\pi - \pi\beta_1^m z^{-1} - \pi\beta_2^m z^{-2}}{2\alpha_0^m A_m \tau (1-z^{-1})}
\end{aligned}$$

Then, the fuzzy controller in the time domain is represented as:

$$u^m(k) = u(k-1) + \frac{\pi}{2\alpha_0^m A_m \tau} d(k) - \frac{\pi\beta_1^m}{2\alpha_0^m A_m \tau} d(k-1) - \frac{\pi\beta_2^m}{2\alpha_0^m A_m \tau} d(k-2) \quad (6-15)$$

6.3 Simulation results and comparisons

The control models are identified based on the experimental rig presented in Chapter 3.5. Inlet solution temperature is regulated by manipulating the chilled water flow rate, which is estimated with a first order plus time delay as:

$$G_{nd}(s) = \frac{-1.666}{21s+1} e^{-5s} \quad (6-16)$$

The relationship between outlet humidity and the solution inlet temperature are approximated with a set of varied proportional models respect to different concentrations, which are listed in Table 6.2. The influences of concentration are enlarged when the operating concentrations have larger differences.

Table 6. 2 Identified LDDS model

Concentration	0.223	0.283
Process	$\frac{0.4720}{12s^2 + 4s + 1} e^{-45s}$	$\frac{0.3864}{12s^2 + 4s + 1} e^{-45s}$
Model		

As a conventional temperature control system, the PID controller generates the control signals based on its proportional, integral and derivative terms. The PID parameters of secondary loop are determined by the method explained in 6.2.1. In order to compare the performances of general and fuzzy-PID, the same parameters of gain and phase margin groups have been utilized in the simulations.

The parameters of the PID controller are listed in Table 6.3.

Table 6. 3 Parameters of the General-PID controllers

Type		K_p	K_i	K_d
General PID				
	Con=0.223	0.0592	0.0148	0.1775
	Con=0.283	0.0753	0.0188	0.2258
Cascade Primary				
Cascade	Con=0.223	0.0822	0.0205	0.2465
Primary	Con=0.283			
Cascade Secondary		-2.5		

Since collecting data from the test rig is restricted by the experimental environments, and contains some unexpected errors, the database of training the fuzzy coefficients is generated from the validated model explained in Chapter 3. Using the method explained in Appendix D [140, 141], the parameters of this fuzzy-PID controller are obtained and listed in Table 6.4 and 6.5.

Table 6. 4 Centers of fuzzy-PID controllers

	Rule1	Rule2	Rule3	Rule4	Rule5	Rule6	Rule7	Rule8
$u^m(k-\tau)$	0.9560	0.7479	0.7493	0.9566	0.9582	0.7480	0.9567	0.7474
$y^m(k-1)$	0.9151	0.7548	0.7537	0.7557	0.7546	0.9138	0.9129	0.9155
$y^m(k)$	0.9120	0.9147	0.7577	0.9131	0.7577	0.7483	0.7501	0.9115

Table 6. 5 Linear parameters of fuzzy-PID controllers

	Rule1	Rule2	Rule3	Rule4	Rule5	Rule6	Rule7	Rule8
α_0	0.9238	1.1289	0.9362	0.9090	0.7645	0.9464	0.7928	1.1406
β_0	0.0338	0.0965	0.0713	0.0627	0.0293	0.0412	-0.0120	0.0660

The simulation results are shown in Figure 6.2 and Figure 6.3. The two fuzzy controllers share the same centers and linear parameters while the parameters of General-PIDs have separated parameters as listed in Table 6.3. Disturbances have been introduced in the inner loop with a step input of 0.2°C at the 5th min of the simulation. The cascade structure successfully removes the some of the disturbances within secondary loop. In this case, the control loop of solution temperature responds faster than that of the dehumidifier tower, which is fit for a cascade structure. The system has a delay of around 1mins and the delay effect of the mathematical model is slightly larger than the identified model. From the results illustrated in these two Figures, the fuzzy controller has faster response and less steady state error, and not needed to be tuned repetitively for models with different parameters.

Three commonly used indexes are used to evaluate the control performances,

Integral Absolute Error (IAE) and Integral Time-weighted Absolute Error (ITAE) and Integral Squared Error (ISE)[142].

$$IAE = \int |e(t)| dt \quad (6-17a)$$

$$ITAE = \int t |e(t)| dt \quad (6-17b)$$

$$ISE = \int e^2(t) dt \quad (6-17c)$$

Figure 6. 2 Comparisons of the control performance (Con=0.223)

Figure 6. 3 Comparisons of the control performance (Con=0.283)

Within a fixed integrals time and same simulation conditions, three parameters described in Eqs.(6-17) are calculated to evaluate the system

performance. The systems with small ISE eliminate large errors quickly, but tolerate small errors for a long period of time. ISE will penalize large errors heavier, and this leads to a fast system responses with oscillation. Compared with ISE, IAE optimized systems specified to reduce oscillation but produce slower response. ITAE has a time factor and weights the steady state errors heavily. ITAE tuning produces systems settling much more quickly than the other two tuning methods but sluggish initial response. The values of all these indexes are enumerated in Table 6.6.

Table 6. 6 Index values of the controllers

Type		IAE	ITAE	ISE
General PID	Con=0.223	0.8573	21.1607	0.1093
	Con=0.283	0.8221	19.7595	0.1024
Cascade Control				
Primary	Con=0.223	0.6527	17.6172	0.0911
	Con=0.283	0.6594	17.2757	0.0885
Fuzzy Model PID				
	Con=0.223	0.5349	14.8183	0.0905
	Con=0.283	0.5916	15.7191	0.0883

Either from Figure 6.2, Figure 6.3 or Table 6.6, it can be observed that the fuzzy-PID controller shows its advantage over its competitors in all cases. The results indicate that fuzzy-PID controller is a suitable control strategy in control the outlet humidity within a regulated working solution concentration range.

6.4 Experimental validation

Experiments have been carried out to fully investigate the whole strategy illustrated in Fig.6.1. During the experimental testing, the whole system is operated with a distributed strategy but without a real distributed arrangement. Experiments are carried out in a room with stable inlet air conditions. The air temperature is around $22.3 \text{ g/kg} \pm 2^\circ\text{C}$ and humidity ratio is around $12 \text{ g/kg} \pm 2 \text{ g/kg}$ dry air. The air velocity is controlled as a constant value of 1.8 m/s during the whole operating period, and the target working solution concentration is 28.5% with $\pm 1\%$ acceptable error. The desiccant mass flow rate is kept at constant values of 40.5 L/min and inlet solution is manipulated to stabilize the outlet air humidity at around 16.5°C .

As shown in Figure 6.4, a 500 minutes experiment is conducted to validate the efficiency of this concentration regulation strategy. The outlet air humidity

is successfully maintained at 6.5 g/kg dry air. The start time for solution transfer is noted with a circle, and this process occurs when the working solution exceeds the capacity of working solution tank. The outlet air humidity is kept at around 6.5 g/kg dry air and the concentration decreasing is totally removed in the experiment. Duration the experiment, the load is varied respected to the occupants in the supply room without any special regulations, but no fresh air is supplied during the test. From Figure 6.4, it can be observed that stable outlet air humidity was maintained in both of the experiment and simulation. Compared with the simulated data, the measured outlet air humidity varies periodically. A reasonable guess is that the strong solution temperature exceeds the normal room temperature a lot, and the charge of desiccant solution tends to bring in a temperature rise in each time the solution charged. The outlet humidity is faster reach 6.7 g/kg dry air due to the solution temperature increase, and the outlet air humidity fluctuates as shown in Figure 6.4. The valve opening time is not evenly distributed during the experiment, this might due to the varied load in the supply room or some errors of the soft-sensing in concentration measurements.

Figure 6. 4 Comparisons of the control performance

Another condition needs discussion is illustrated as Figure 6.5. The strong solution is kept at a low temperature to remove the temperature effect revealed in Figure 6.4, which can be observed from Figure 6.5 after the 30mins. In this part of experiment (from 30 min to 100 min), the regulation is normal and the control effective is stable with only small disturbances when the strong solution is supplied into the tank. Another issue need to be discussed can be observed in the first 30mins in Figure 6.5. Sometimes, the performance is not good when the system is totally relying on regulating the desiccant temperature. A possible explanation is the temperature regulation controller comes across with a high

sensitive control region of which is associated with the water pressure in the pipe. It needs a carefully selection of the accurate of the regulation valve based on the water pressure inside the tube, or it will easily generate a condition as the initial 30 mins. Moreover, an improvement of the algorithm should be considered to control the solution temperature by considering the differences of water pressure in the chilled water pipes.

Figure 6. 5 Comparisons of the control performance

6.5 Summary

In this chapter, the whole strategy was tested on a platform with distributed operation mechanism. A fuzzy-PID controller regulated the outlet air humidity by manipulated the chilled water volume flow rate has been developed and validated. The comparisons in the simulations convinced the superiority of Fuzzy-PID controller in three indexes: IAE, ITAE and ISE. The combination of all the modules introduced in this thesis can worked together and give satisfied performances. Some new problems have come to the light to further improve the dehumidification performance in a distributed LDDS, and will be presented in Chapter 7.

Chapter 7. Conclusions and Future Work

7.1 Conclusions

If properly designed and optimized, distributed LDDS can be applied to buildings to reduce the cost of implementation and operation, and improve the energy efficiency in cooperation with the conventional air-conditioning system. The number of regenerators can be reduced to one, and the low-grade heat available in buildings can be used within this framework.

This thesis focused on solving the problems associated with the application of distributed LDDS. In summary, the following issues have been investigated to promote the distributed operation scheme: a model focused on unstable working solution concentration, a strategy for measuring the real-time working solution concentration in the major components, a concentration regulation strategy to confine the working solution concentration of the dehumidifier within a certain range, and the optimal energy-saving working solution concentration pairs. All these modules have been combined with the fuzzy-PID controller to adjust the control performance and analyzed in this thesis.

The main contributions of this thesis are addressed as following:

1.A dynamic model to address the concentration profiles has been proposed.

A strong solution buffer and a regulating valve were integrated with the dehumidifier to provide a stable working solution concentration to facilitate the distributed operation. A new mathematical model was developed to describe the heat and mass transfer rate together with the dynamic profiles of concentration during the operation, including the moisture absorption, strong solution charging, solution mixing, circulating, and excavating. The predictive ability of this model was validated by experiments and proved inconsistent with the various solution temperatures and concentrations.

2.Soft sensors were developed to detect the working solution concentration in the dehumidifier and regenerator.

Model-based soft sensors of the dehumidifier and regenerator were designed to detect the working solution concentrations of the main working components in distributed operating LDDS. The soft sensors were well tuned, and experiments had been conducted to validate their accuracy in different working

conditions. The dehumidifier requires high accuracy in concentration detection, while the regenerator needs a concise structure to monitor the concentration to stop the regeneration. Therefore, the regenerator soft sensor focused on simplifying the structures while the measurement accuracy of the dehumidifier soft sensor was validated in the various environments. The proposed soft sensors have a RMSRE lower than 0.02.

3.Regulation of the working solution concentrations in the dehumidifier.

A concentration regulation method for the buffer-integrated dehumidifier was proposed and proved effective in regulating the working solution concentration. In the simulations with and without disturbances, this strategy showed its good performances in regulating the working solution concentration as well as the outlet air humidity. Experimental studies on an actual LDDS were carried out to further validate its effectiveness. With the proposed method, the working solution concentration problem related to the distributed LDDS had been solved, and steps forward to the generalization of this novel operating mechanism.

4.Energy-orientated optimization of the working solution concentration pairs.

The relations between the solution concentration and energy consumption of the LDDS were investigated. The energy usage of the components and processes with different operating concentrations was calculated with the validated models. A genetic algorithm was used to obtain the optimal combination of weak and strong concentrations, the solution mass flow rate in the dehumidification side, and the chilled water mass flow rate. The component and overall energy consumptions at the optimal operating concentration were discussed and compared. The results suggested that the appropriate operating concentrations in the dehumidifiers and regenerator can the energy consumption while satisfying the outlet air requirements. The optimized concentration pairs were used as the set point in the humidity control strategy proposed in this thesis.

5.Fuzzy-PID controller and humidity control

When the working solution concentration was regulated within a certain range, a fuzzy-PID controller was implemented to fine tune the outlet air humidity by manipulating the solution inlet temperature. The controller was developed based on a T-S fuzzy model, and the K_p , K_i , and K_d parameters

varied according to previous and current input and output variables. Compared with conventional PID controllers, the fuzzy-PID controller can be easily applied to different situations without specific tuning.

6. Combination and validation of previously introduced modules

By combining previously introduced modules, a strategy for the continuous operation of distributed LDDS was devised. The desiccant solution concentrations of the two primary components was measured and regulated to the range generated with the proposed model and the optimizer. Indices, such as IAE, ITAE, and ISE, were used to evaluate the control performance of the combined modules in the simulations. With some simplifications, these modules were applied to the test rig following the distributed operating strategy to validate this control strategy comprehensively.

7.2 Future work

Despite all the achievements stated in this thesis, there are still some gaps in fulfilling the goal of promoting the distributed operating system. It would be valuable to make further efforts in this area. To throw some light, few recommendations are specified as follows:

1. The experimental analysis in Chapter 6 covers some problems on the chilled water regulation. Since the chilled water sources are the building chilled water, chiller system or heat pump, the water pressure in the pipes should be considering carefully concerning the locations of the individual dehumidifiers to satisfy the control accuracy. High chilled water pressure inside the piping system might increase the control difficulties on account of the decreasing of control accuracy of the regulating valves. For instance, a LDDS with multiple dehumidifiers utilizing the building chilled water as the cooling source, the dehumidifier in the basement bears significant large water pressure than the one on the roof top if applying the building chilled water system. Therefore, different control strategy should be considered due to the one at the basement needs accurate valves to achieve the same performance as the one on the rooftops with the current strategy.

2. The regenerator operates in a high-temperature environment, and the desiccant solution in the regenerator is typically at a temperature above 48°C. Though the desiccant solution has been transferred and stored in the solution

tanks and got chilled, sometimes, the solution in the buffer is still at an obviously higher temperature. Models should be developed to describe this including the transfer time, storage time, and temperature variations in the storage facilities owing to the sensitivity of the dehumidification performance on the solution temperature.

3. For multiple dehumidifiers in distributed operational mode, the number of dehumidifiers should be considered carefully in case the regenerator cannot satisfy all the components. Clear mathematical relations should be derived to determine the design parameters for the regenerator and the numbers of dehumidifiers by considering the different groups of cooling sources, heating sources, location, and available piping. The energy consumption should also be investigated carefully to avoid energy waste in the solution transfer when considering the complex requirements and the building environment.

4. A combination of a concentration regulator and a fuzzy-PID controller has been employed to regulate the outlet air humidity of the dehumidifier in this thesis. The outputs of dehumidifier can reach the required set point even in conditions with disturbances. However, it still leaves room for improvement: the overshoots caused by the solution mixing can be reduced or even eliminated, and the fluctuations reflected in the experiment can be avoided. Given that detailed mathematical models have been developed for the system, other model-based sophisticated control strategy should be investigated to give further improvement of the control performances in future study.

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Appendix A

The dehumidifier mass transfer coefficient can be expressed by Eq.(A-1) [69]:

$$K_G = \frac{1}{\frac{1}{k_a} + \frac{1}{Hk_s}} \quad (\text{A-1})$$

where k_a is the gas phase convention mass transfer coefficient, k_s is the liquid phase convention mass transfer coefficient, and these two parameters can be written as Eq.(A-2) and (A-3).

$$k_a = a_1 \left(\frac{4\dot{m}_a}{\alpha_t \mu_a \pi D^2} \right)^{e_1} \left(\frac{\mu_a}{\rho_a D_a} \right)^{f_1} (\alpha_t D_p)^{g_1} \frac{\alpha_t D_a}{RT_a} \quad (\text{A-2})$$

$$k_s = a_2 \left(\frac{4\dot{m}_s}{\alpha_\omega \mu_s \pi D^2} \right)^{e_2} \left(\frac{\mu_s}{\rho_s D_s} \right)^{f_2} (\alpha_t D_p)^{g_2} \left(\frac{\rho_s}{\mu_s g} \right)^{j_2} \quad (\text{A-3})$$

where α_t is the specific surface area, α_ω is the wetted specific surface area, D_p is the packing material nominal size. D_a , ρ_a , μ_a and D_s , ρ_s , μ_s are the diffusivity, density, viscosity of process air and desiccant solution, respectively [69, 78].

Therefore, the coefficients can be simplified as:

$$k_a = a_1 (\dot{m}_a)^{j_1} \frac{1}{T_{a,in}} \quad (\text{A-4a})$$

$$k_s = a_2 (\dot{V}_s)^{j_2} (\tilde{\rho}_s)^{j_3} \quad (\text{A-4b})$$

Since the air density does not change much in the operating period of dehumidifier, and the volume flow rate of air is generally determined by the occupants, the dynamic characteristic of $\dot{m}_a$ will not be considered for simplification.

By substituting Eqs. (A-4) into Eq. (A-1), we can get Eq.(A-5) to describe the mass transfer coefficient on the contact surface.

$$K_G = \frac{\hat{c}_1 (\dot{V}_s)^{\hat{c}_3} (\tilde{\rho}_{s,i})^{\hat{c}_4}}{1 + \hat{c}_2 T_{a,in,i-1} (\dot{V}_s)^{\hat{c}_3} (\tilde{\rho}_{s,i})^{\hat{c}_4} (\dot{m}_a)^{\hat{c}_5}} \quad (\text{A-5})$$

In the steady state heat and mass transfer coefficients, the density and

specific heat are regarded as constants for simplification. The $\tilde{\rho}_{s,i}$ here cannot be considered as a constant since it is a function of solution concentration and temperature, which are two control variables varied with the system operation. The density here will be regarded as a function both in the identification and application processes. Moreover, the database utilized to identify the parameters is built up with the data collected in the conditions with dynamic variations in temperatures and concentrations to increase the sensitivities on the control variables during the parameter training [69, 103].

The modified mass transfer rate in a specific volume can be calculate with Eq.(A-6) [143-145]:

$$K'_G = \frac{\alpha \cdot \hat{c}_1 (\dot{V}_s)^{\hat{c}_3} (\tilde{\rho}_{s,i})^{\hat{c}_4}}{1 + \hat{c}_2 T_{a,in,i-1} (\dot{V}_s)^{\hat{c}_3} (\tilde{\rho}_{s,i})^{\hat{c}_4} (\dot{m}_a)^{\hat{c}_5}} \quad (\text{A-6})$$

where α is the effective contact area ratio of the structured packing.

The heat transfer rate can be described as:

$$\dot{Q} = \frac{T_{a,in} - T_{s,in}}{R_h} \quad (\text{A-7})$$

where $T_{a,in}, T_{s,in}$ are the inlet temperature of process air and the inlet desiccant solution. R_h is the thermal resistance of the complete heat transfer procedure [69, 78].

The overall thermal resistance R_h can be expressed as:

$$R_h = R_a + R_s \quad (\text{A-8})$$

of which R_a is the air side convention and R_s is the solution convention[69, 78].

In dehumidifier, forced convection happens between the two working fluids. Heat transfer coefficient can be expressed as Eq. (A-9), with the heat transfer coefficients h , the packing diameter D , the fluid density ρ , velocity ν , specific heat c_p , viscosity μ , and thermal conductivity as parameters [69, 78].

$$\frac{hD}{k} = C \left(\frac{D\rho\nu}{\mu} \right)^e \left(\frac{c_p\mu}{k} \right)^f \quad (\text{A-9})$$

where the μ and k are approximately constants if the temperature change of

fluid is relative small. In dehumidifier, D is a constant value after the packing tower is built.

The Eq. (A-9) can be rewritten as:

$$h = C \left(\frac{D \tilde{\rho} \nu}{\mu} \right)^e \left(\frac{\tilde{c}_p \mu}{k} \right)^f \frac{k}{D} = C \left(\frac{D}{\mu} \right)^e \left(\frac{\mu c_p}{k} \right)^f \frac{k}{D} (\tilde{\rho} \nu)^e = b (\tilde{c}_p)^f (\tilde{\rho} \nu)^e \quad (\text{A-10})$$

The parameters $\tilde{c}_p$ and $\tilde{\rho}$ cannot be considered as a constant because the two parameters vary with temperature and concentration.

The overall heat resistance is:

$$R_h = \frac{1}{h_s A_s} + \frac{1}{h_a A_a} \quad (\text{A-11})$$

The heat transfer rate in a specific volume can be calculated as Eq. (A-12), where α is the effective contact area ratio of the structured packing.

$$h' = \frac{\alpha \cdot \hat{c}_6 \left(\tilde{\rho}_{s,i} \dot{V}_s \right)^{\hat{c}_8} \left(\tilde{c}_{ps,i} \right)^{\hat{c}_9}}{1 + \hat{c}_7 \left(\frac{\tilde{\rho}_{s,i} \dot{V}_s}{\dot{m}_a} \right)^{\hat{c}_8} \left(\tilde{c}_{ps,i} / \tilde{c}_{pa,i} \right)^{\hat{c}_9}} \quad (\text{A-12})$$

Both of the $\tilde{\rho}_{s,i}$ and $\tilde{c}_{ps,i}$ are considered as functions of solution temperature and concentration in both of the identification and application processes utilizing the relations explain in [44].

Appendix B

The process of water moisture migrates between the two working fluids can be predicted mathematically by a mass transfer model [69]:

$$\dot{m}_{D\&R} = K_G \left| p_{a,in} - p_{s,in}^* \right| \quad (\text{B-1})$$

where $\dot{m}_D$, K_G , $p_{a,in}$ and $p_{s,in}^*$ are the mass transfer rate between the two working fluids, the mass transfer coefficient, water vapor pressure of inlet air and surface water vapor pressure of desiccant solution, respectively.

The mass transfer coefficient can be expressed as [69]:

$$K_G = \frac{\hat{c}_1 (\dot{m}_s)^{\hat{c}_3}}{1 + \hat{c}_2 T_{a,in} (\dot{m}_s)^{\hat{c}_3} (\dot{m}_a)^{\hat{c}_4}} \quad (\text{B-2})$$

where $\dot{m}_a$, $\dot{m}_s$, $T_{a,in}$ are the mass flow rate of air, mass flow rate of the solution

and inlet air temperature, respectively. The parameters $\hat{c}_1 - \hat{c}_4$ in Eq. (B-2) can be identified using experimental data by Levenberg–Marquardt method [103].

The water vapor pressure of inlet air $p_{a,in}$ can be calculated based on the definition of relative humidity, as:

$$p_{a,in} = RH_{a,in} p_{sat,in} \quad (B-3a)$$

with

$$p_{sat,in} = a_0 T_{a,in}^2 + a_1 T_{a,in} + a_2 \quad (B-3b)$$

where $RH_{a,in}$, p_{sat} are the relative humidity, the saturated water vapor pressure of the inlet air, and $a_0 - a_2$ are the fitting parameters [146]. The fitting parameters of dehumidifier and regenerator are different from each other, and the values can be obtained from [69] and [78], respectively.

On the other hand, a method to calculate surface water vapor pressure of the desiccant solution $p_{s,in}^*$ is given as [44]:

$$p_{s,in}^* (c_{D\&R}, T_{s,in}) = p_{H_2O} (T_{s,in}) f(c_{D\&R}, T_{s,in}) \quad (B-4)$$

where $c_{D\&R}$, $T_{s,in}$, $p_{H_2O} (T_{s,in})$, $f(c_{D\&R}, T_{s,in})$ are mass fraction of desiccant solution concentration, the temperature of inlet solution, the surface vapor pressure of ordinary water and correction function, respectively. The detailed derivation of $p_{H_2O} (T_{s,in})$ and $f(c_{D\&R}, T_{s,in})$ are provided in [44].

The mass transfer between the two working fluids can be evaluated through monitoring the amount of removed moisture for the given mass flow rate of the air by:

$$\dot{m}_{D\&R} = \frac{|HR_{a,in} - HR_{a,out}|}{\alpha \cdot V} \dot{m}_a \quad (B-5a)$$

with [147]:

$$HR = \frac{0.622 p_{sat,x} \cdot d_{a,x}}{101.325 - d_{a,x} \cdot p_{sat,x}} \quad (B-5b)$$

where $HR_{a,out}$, $HR_{a,in}$, α , V are the inlet air humidity ratio, the outlet air humidity ratio, the specific surface area in the structure packing and the dehumidifier tower volume, respectively. The inlet and outlet air humidity

ratios $HR_{a,in}$ and $HR_{a,out}$ can be calculated from Eq. (B-5) through $d_{a,in}$, $p_{sat,in}$ and $d_{a,out}$, $p_{sat,out}$, respectively, where the value of $p_{sat,in}$ can be obtained by Eq. (B-3b), and $p_{sat,out}$ can be calculated using the same equation with the outlet air temperature $T_{a,out}$. The product $\alpha \cdot V$ is the equivalent contact area for the two working fluids inside the dehumidifier with structure packing.

Thus, both of the Eq. (B-1) and Eq. (B-5) can be utilized to estimate the dehumidification rate with different available input variable groups, by combined them, we can obtained Eq.(4.7).

Appendix C

Figures of fuzzy rules for different models.

Figure C. 1 ANFIS membership functions

Figure C. 2 Mo-ANFIS membership functions

Figure C. 3 Mo-Opt-ANFIS membership functions

*of which the Gene1, Gene2, Gene3, Gene4 represent $p_{a,in}$, $T_{a,in}$, G_1 and G_2 , respectively.

The fuzzy rules and centers are displayed as Table C.1 and Table C.2.

Table C. 1 Soft sensing fuzzy rules of dehumidifier

	Gene1	Gene2	Gene3	Gene4	Concentration
Rule1	1	1	1	1	1
Rule2	1	1	1	2	2
Rule3	2	2	2	1	3
Rule4	3	1	3	3	4
Rule5	4	1	1	3	5
Rule6	5	3	4	4	6
Rule7	2	4	2	3	7
Rule8	5	4	3	2	8
Rule9	1	5	3	1	9
Rule10	6	5	1	5	10
Rule11	7	6	5	6	11
Rule12	2	4	2	7	12
Rule13	8	4	5	8	13
Rule14	8	2	7	9	14

Table C. 2 Cluster centers of dehumidifier soft-sensor

	Gene1	Gene2	Gene3	Gene4
Cluster1	2.04	18.94	-3.62	2.12
Cluster2	2.55	15.75	-6.26	2.00
Cluster3	2.09	12.93	-4.78	2.53

Cluster4	1.84	16.50	-13.4	4.08
Cluster5	2.65	17.31	-9.46	4.18
Cluster6	1.53	18.18	-10.81	5.27
Cluster7	1.99	--	--	2.33
Cluster8	2.24	--	--	4.64
Cluster9	--	--	--	4.42

*of which the Gene1, Gene2, Gene3, Gene4 represent $p_{a,in}$, $T_{a,in}$, G_1 and G_2 , respectively.

Appendix D

Randomly initialize a fuzzy membership matrix U^0 for the data samples:

$$U^0 = [\mu^{0,m}(\mathbf{V}(k))]_{N \times Num} = \begin{bmatrix} \mu^{0,1}(\mathbf{V}(1)) & \mu^{0,1}(\mathbf{V}(2)) & \cdots & \mu^{0,1}(\mathbf{V}(Num)) \\ \mu^{0,2}(\mathbf{V}(1)) & \mu^{0,2}(\mathbf{V}(2)) & \cdots & \mu^{0,2}(\mathbf{V}(Num)) \\ \vdots & \vdots & \ddots & \vdots \\ \mu^{0,N}(\mathbf{V}(1)) & \mu^{0,N}(\mathbf{V}(2)) & \cdots & \mu^{0,N}(\mathbf{V}(Num)) \end{bmatrix} \quad (D-1)$$

where $0 \leq \mu^{0,m}(\mathbf{V}(k)) \leq 1$ denotes as the initialized fuzzy membership value of $\mathbf{V}(k) = [\mathbf{Z}(k) \ \mathbf{Y}(k)]$ in m th cluster, and $\sum_{l=1}^N \mu^{0,l}(\mathbf{V}(k)) = 1$ for $k = 1, \dots, Num$. Based on U^0 , the center of the m th cluster, can be calculated by

$$\mathbf{V}_c^m = \frac{\sum_{k=1}^{Num} \mathbf{V}(k) \cdot (\mu^{0,m}(\mathbf{V}(k)))^2}{\sum_{k=1}^{Num} (\mu^{0,m}(\mathbf{V}(k)))^2} \quad (D-2)$$

where $\mathbf{V}_c^m$ consist the center of input and output vectors in m th cluster.

Based on the centers $\mathbf{V}_c^m$ ($m = 1, \dots, N$), the fuzzy covariance matrix for the m th cluster, denoted by F^m , can be computed by

$$F^m = \frac{\sum_{k=1}^{Num} (\mu^{0,m}(\mathbf{V}(k)))^2 \cdot (\mathbf{V}(k) - \mathbf{V}_c^m)^T \cdot (\mathbf{V}(k) - \mathbf{V}_c^m)}{\sum_{k=1}^{Num} (\mu^{0,m}(\mathbf{V}(k)))^2} \quad (D-3)$$

Each fuzzy cluster has its own norm-inducing matrix denoted as A^m , and the determinant value is explained as:

$$A^m = \det(F^m)^{m/(win+wout+2)} \cdot (F^m)^{-1} \quad (D-4)$$

Based on A^m , the adaptive distance between $\mathbf{V}(k)$ and $\mathbf{V}_c^m$, denoted by $\bar{D}(\mathbf{V}(k), \mathbf{V}_c^m)$, can be yielded.

$$\bar{D}(\mathbf{V}(k), \mathbf{V}_c^m) = (\mathbf{V}(k) - \mathbf{V}_c^m) \cdot A^m \cdot (\mathbf{V}(k) - \mathbf{V}_c^m)^T \quad (\text{D-5})$$

Based on the adaptive distances $\bar{D}(\mathbf{V}(k), \mathbf{V}_c^m)$ ($m=1, \dots, N$), the updated fuzzy membership of $\mathbf{V}(k)$ in m th cluster C^m can be calculated by

$$\mu^m(\mathbf{V}(k)) = \begin{cases} \frac{1}{\sum_{s=1}^N \bar{D}(\mathbf{V}(k), \mathbf{V}_c^s)}, & \text{if } \text{all } \bar{D}(\mathbf{V}(k), \mathbf{V}_c^s) \neq 0, \\ & s=1, \dots, N \\ 0, & \text{if } \text{any } \bar{D}(\mathbf{V}(k), \mathbf{V}_c^s) = 0, \\ & s=1, \dots, N, s \neq m \\ 1, & \text{if } \bar{D}(\mathbf{V}(k), \mathbf{V}_c^s) = 0 \end{cases} \quad (\text{D-6})$$

then the updated fuzzy membership matrix can be obtained as:

$$U = [\mu^m(\mathbf{V}(k))]_{N \times \text{Num}}.$$

The calculation will be terminated when $\|U - U^0\| < \varepsilon$, otherwise, let $U^0 = U$, repeat the steps explained in this section.

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