Energy and Buildings 129 (2016) 215–226

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Dehumidifier desiccant concentration soft-sensor for a distributed operating Liquid Desiccant Dehumidification System

Qiong Wu [a,b], WenJian Cai [c,*], Xinli Wang [c], Anutosh Chakraborty [d]

[a] Interdisciplinary Graduate School, Nanyang Technological University, Singapore
[b] Energy Research Institute at Nanyang Technological University, Singapore
[c] EXQUISITUS, Centre for E-City, School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore
[d] School of Mechanical & Aerospace Engineering, Nanyang Technological University, Singapore 639798, Singapore

A R T I C L E I N F O

Article history:
Received 12 April 2016
Received in revised form 13 July 2016
Accepted 25 July 2016
Available online 26 July 2016

Keywords:
LDDS
Dehumidifier
Concentration
Physical model
Soft-sensor
ANFIS
GA

A B S T R A C T

Distributed operating of Liquid Desiccant Dehumidification System (LDDS) increases the flexibility in system operation, allowing one regenerator to handle multiple dehumidifier units. To meet the requirement of this operating scheme, a soft-sensor is developed for the real-time measurement of the desiccant solution concentration. A physical model of mass transfer rate in the dehumidifier is employed to reduce the number of input variables of the Adaptive Network-based Fuzzy Inference Systems (ANFIS) structure, and then the Genetic Algorithm (GA) is selected to further simplify the fuzzy interference with a constrained objective function. Owing to these simplifications, an accurate model-based soft-sensor with a concise ANFIS structure has been formulated. Concentration values obtained by this soft-sensor are validated by experimental data to prove its effectiveness and results show that the proposed method can acquire the online concentration accurately which will be beneficial in the system performance monitoring, control or optimization.

1. Introduction

During the past decades, energy conservation and occupant comfort have become two major concerns in air-conditioning industries. Among several parameters to be controlled for Indoor Environment Quality (IEQ), humidity is critically important in terms of human comfort and health. Compared with the conventional method of dealing with the latent load through overcooling and reheating processes, Liquid Desiccant Dehumidification Systems (LDDS) have certain advantages: 1) achieving low humidity level with relatively low energy consumption; 2) employing desiccant solution as working fluids to improve supply air quality; 3) independent control of air temperature and humidity; 4) potential to apply low grade energy, such as solar energy and geothermal energy. These merits make LDDS more attractive in recent years.

Considerable research works for LDDS have been reported on the system performance analysis [1–3], system structure reconstruction [4–6] and dehumidification/regeneration processes modeling [7–9]. As an important factor, the concentration of liquid desiccant solution has been investigated by some researchers. Chen et al. [10] conducted a research on the performance of a dehumidifier operated in low temperature and low desiccant concentration. In order to make the condensation heat in a vapor compression system enough for the desiccant solution regeneration, a working concentration 25.4%–26.9% is suggested to get a satisfied coefficient of performance. She et al. [11] explicated the most appropriate working concentration through the performance analysis of their system. The concentrations of commonly used liquid desiccant, such as LiCl, LiBr, $CaCl_2$, under the standard condensing temperature were discussed.

The desiccant concentration in conventional LDDS is controlled through regeneration temperature and constant exchange of strong and weak solutions between regenerator and dehumidifier [12]. However, this kind of solution exchanging is not appropriate for building applications since the dehumidifiers are generally located at different floors with different loads and requirements. As an attractive topic recent years, numerous efforts have been devoted to implement LDDS in the industrial or commercial buildings to handle the latent load [13–15], and distributed operating LDDS is one of the improved applications. A 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. In distributed operating LDDS, each dehumidifier is integrated with a

* Corresponding author.
E-mail address: ewjcai@ntu.edu.sg (W. Cai).

http://dx.doi.org/10.1016/j.enbuild.2016.07.054
0378-7788/

Nomenclature

$c_1 - c_4$	Parameters of mass transfer model
con_{de}	Solution concentration in dehumidifier (%)
$\phi_{a,in}$	Relative humidity of inlet process air
$\phi_{a,out}$	Relative humidity of outlet process air
$\phi_{a,x}$	Relative humidity of process air at position x
$T_{a,in}$	Inlet air temperature (°C)
$T_{a,out}$	Outlet air temperature (°C)
$T_{s,in}$	Inlet solution temperature (°C)
$T_{s,out}$	Outlet solution temperature (°C)
K_G	Mass transfer coefficient (kg/(m^2 s pa))
$\dot{m}_s$	Mass flow rate of desiccant solution in dehumidifier (kg/s)
$\dot{m}_a$	Mass flow rate of the air in dehumidifier (kg/s)
$\dot{m}_{de}$	Dehumidifier mass transfer rate (kg/(m^2 s))
$p_{a,in}$	Water vapor pressure of inlet air in the dehumidifier (pa)
$p^*_{s,in}$	Water surface vapor pressure of desiccant solution in the dehumidifier (pa)
$p_{sat,in}$	Saturated water vapor pressure of the inlet air (pa)
$p_{sat,out}$	Saturated water vapor pressure of the outlet air (pa)
$p_{sat,x}$	Saturated water vapor pressure of the air at x (pa)
$HR_{a,in}$	Inlet air humidity ratio (g/kg dry air)
$HR_{a,out}$	Outlet air humidity ratio (g/kg dry air)
α	Specific surface area (m^2/m^3)
V	Dehumidifier tower volume/(m^3)

strong solution buffer which continuously supplies strong solution to the dehumidifier to maintain the working concentration. This mixing process is to control the concentration and consequently the treated air with constant humidity ratio. In such situation, a reliable, real-time desiccant concentration sensor becomes vitally important.

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 hours accumulating, re-calibration is needed which will interrupt the system operation. Moreover, the complexity mathematical form of the commonly utilized liquid desiccant solution properties [16] 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. [17] 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. [18] 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. [19] developed a method for multi-model soft sensing modeling based on time variant process.

As a hybrid intelligent system, ANFIS integrates the advantage of learning in artificial neural network and employing fuzzy reasoning, which makes it an appropriate choice in soft-sensor development [20]. Chong et al. [21] designed a soft-senor for dye concentration, and Ghiasi et al. [22] developed a soft-sensor for CO_2 concentration detection in a CO_2 capture process, both utilizing ANFIS framework.In the development of ANFIS model, fuzzy rule identification is an important topic, and genetic algorithm (GA) attracts greater research effort than other approaches [23–25]. GA, a stochastic optimization technique [26], can optimize the ANFIS structure. Dahal et al. [25] presented a GA based learning approach for ANFIS. Tahmasebi et al. [27] 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 this paper, a soft-sensor is developed to measure the working concentration of liquid desiccant in the dehumidifier of a distributed operating LDDS in real time. The number of input variables of this soft-sensor is reduced by physical model correlation, and then the ANFIS framework is optimized with GA by a constraint objective function to form a concise but accurate structure. The weight parameters are tuned with experimental data. Finally, this well-tuned soft-sensor is implemented on the dehumidifier designed for distributed operation, and validated with experimental data.

2. Distributed LDDS working principles

The distributed operation approach allows the LDDS to handle multiple dehumidifiers with one regenerator which provides a possibility for centralized regeneration of desiccant to be supplied to dehumidifiers running in different places. Furthermore, this method avoids continuously exchange between dehumidifier and regenerator, and the replacement of the desiccants only occurs when the limit is reached to avoid the energy waste and improve the system efficiency. The schematic diagram of the system under study is shown as in Fig. 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 over 10% higher concentration than the highest working 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 can 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.

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 Fig. 2, where a strong solution buffer and a regulating valve are integrated with a dehumidifier to provide a stable working con-