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Dynamic modeling of a liquid desiccant dehumidifier ☆

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HIGHLIGHTS

- A simplified dynamic model is proposed for a liquid desiccant dehumidifier.
- The heat and mass transfer processes are analyzed in detail.
- A combined LMA and EKF algorithm is used for the parameters estimation.
- The modeling quality is validated through experiment.
- The proposed model can be easily linearized into the state space form.

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ABSTRACT

The liquid desiccant dehumidification system is becoming a hotspot in air dehumidification due to its promising prospects. Many models have been reported in the literature, but they are rarely applicable to control design due to various reasons. In this paper, a simplified dynamic model of liquid desiccant dehumidifier is proposed from a control point of view based on the heat and mass transfer principles, where the spatial differentials of fluid properties are approximated by discretization and dynamic interaction along the flow direction. Unknown model parameters are first estimated from static experimental data through the Levenberg-Marquardt algorithm and then refined from dynamic experimental data through the extended Kalman filter. The proposed model performs well in the experimental validation and is expected to be applied in a future control design and fault diagnosis application.

1. Introduction

In the modern society, humans spend most of their time indoor and the building air conditioning systems consume enormous energy to maintain a comfortable environment. According to the ASHRAE 62.1 standards [1], enough fresh air should be delivered to conditioned rooms to cover occupants' emissions and achieve acceptable indoor air quality (IAQ) to keep them healthy and productive. Based on a building energy benchmarking report in [2], up to 37% electricity is consumed by building systems in developed countries like Singapore, where half is used for indoor occupant thermal comfort. Thus, energy efficiency in buildings has become an important target for a low carbon footprint and sustainable future, which is excepted to be achieved through technology upgrading. Air dehumidification is indispensable to air conditioning, especially in the tropics. In building systems, heat, ventilation and air conditioning (HVAC) system has been widely used since the early last century [3], where cooling-based air dehumidification is adopted [4]. The supply air is firstly cooled below its dew point to liquefy the redundant moisture and then reheated to required temperature before supplying to conditioned rooms. This scheme is effective but wastes lots of energy in air overcooling and reheating. As an alternative approach, liquid desiccant dehumidification system (LDDS) has arisen in the past two decades [5,6], where the moisture is directly absorbed by its liquid desiccant with low vapor pressure. This chemical-based scheme is popular for its merits including (1) great energy saving by using renewable or low grade energy; (2) flexibility in achieving independent control on air temperature and humidity; (3) great environmental-friendliness without discharging pollution; and (4) reducing the propagation of bacteria and mildew in equipment under dry ambience.

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Nomenclature

$a_1 \sim a_3$	constant parameters of the cooler (dimensionless)
$c_1 \sim c_3$	lumped parameters of the cooler (dimensionless)
$d_1 \sim d_8$	lumped parameters of the dehumidifier (dimensionless)
$\beta_1 \sim \beta_6$	desiccant pressure coefficients (dimensionless)
A, D	geometric parameters of the cooler (m^2, m)
A_c	cross-sectional area of the dehumidifier (m^2)
C_p	fluid specific heat capacity (J/(kg °C))
h	heat transfer coefficient (W/°C)
H_c	heat transfer coefficient of the cooler (W/°C)
H_h	heat transfer coefficient of the dehumidifier (W/°C)
H_m	mass transfer coefficient of the dehumidifier (kg/Pa)
k	fluid thermal conductivity (W/(m^2 °C))
L_w	water heat of evaporation (J/kg)
$\dot{m}$	mass fluid flow rate (kg/s)
M	mass constant (kg)
N	block number of the dehumidifier (dimensionless)
P_0	standard atmospheric pressure ($P_0 = 101$ kPa)
P_a	water vapor pressure of process air (Pa)
P_s	equivalent water vapor pressure of desiccant solution (Pa)
P_r	Prandtl number (dimensionless)
R_e	Reynolds number (dimensionless)
T_a	process air temperature (°C)
T_{ai}	inlet air temperature of the dehumidifier (°C)
T_{ao}	outlet air temperature of the dehumidifier (°C)
T_s	desiccant temperature (°C)
T_{si}	inlet desiccant temperature of the cooler (°C)
T_{so}	outlet desiccant temperature of the cooler (°C)
T_w	chilled water temperature (°C)
T_{wi}	inlet water temperature of the cooler (°C)
T_{wo}	outlet water temperature of the cooler (°C)
u	fluid velocity (m/s)
$\dot{V}$	volume fluid flow rate (m^3/s)
ρ	fluid density (kg/m^3)
μ	fluid viscosity (Pa s)
ω_a	process air humidity (kg/kg)
ω_{ai}	inlet air humidity of the dehumidifier (kg/kg)
ω_{ao}	outlet air humidity of the dehumidifier (kg/kg)
ω_s	desiccant concentration (%)

Subscripts

a	process air
s	desiccant solution
w	chilled water
$,i$	the ith block

According to a technical review, LDDS can save about 40% energy in comparison to the conventional HVAC system [6]. However, its application is limited by few available control strategies investigated in [7–9]. Moreover, highly efficient LDDS controller is required to regulate both its performance and consumption, but this part is seldom addressed in the literature. Though various models have been reported, they rarely illustrate how the control inputs dynamically affect its outputs. Besides this, some models for accurate output prediction are limited by their model complexity and heavy computation load. Moreover, both controllable and uncontrollable inputs exist in LDDS, whose effects on system should be separately studied. For those uncontrollable inputs like inlet air temperature and humidity, their negative effects should be rejected through the system control. To cater for above requirements, a new dynamic model of LDDS is needed.

Foreseeing its promising prospects, many theoretical and experimental studies on LDDS have been reported in the literature, which mainly focus on equipment design [10,11], performance analysis [12–14] and process modeling, where the developed models can be grouped into finite difference model, effectiveness NTU model and empirical model. The finite difference model has been studied in-depth for its accuracy. Öberg and Goswami [15] proposed a theoretical model for a counter-flow liquid desiccant dehumidifier, where the model was derived from detailed experimental investigations on the heat and mass transfer processes and agreed well with the experimental findings. Audah et al. [16] tried to study the optimal conditions of a solar-powered liquid desiccant system, and they proposed a difference model through Runge-Kutta scheme by integrating moisture and energy balance within the packed bed and achieved good validation in the experiment. Similarly, Lazzarin et al. [17], Peng and Zhang [18] and Liu et al. [19] adopted the difference model in their studies. Chengqin et al. [20] described the system process of a dehumidifier through two coupled ordinary differential equations, whose analytical solutions were derived under a linear approximation assumption and gave more accurate model predictions. The finite difference models were mainly used for performance analysis and optimization. However, they are seldom used for control design due to their complex model development and intensive iteration in output prediction. Besides this, some detailed information on packed beds or fluid properties may be required in the model development which are not available in practice. As for the effectiveness NTU model, Stevens et al. [21] applied it to describe the heat and mass transfer processes in a liquid desiccant heat/mass exchanger, where the Number of Transfer Units (NTU) and the effectiveness of dehumidifier were first computed and then used to calculate the outlet air humidity. Ren [22] improved the effectiveness NTU model by using the perturbation technique to deal with the nonlinear effects on air humidity and enthalpy. Their model could beat most simple NTU models in the validation. In addition, the NTU model is also found in [23,24], which, in comparison to the finite difference model, can greatly reduce the computation load but would result in less accurate prediction. In practice, the empirical models are also popular in LDDS investigations. Gandhidasan [25] proposed a simplified model to predict the moisture removal rate of dehumidification through the dimensionless pressure and temperature differences, while Joon-Young et al. [26] proposed a simplified linear equation to describe the dehumidification effectiveness of absorbers based on the statistical analysis on operational data which is applicable within given ranges. Yang et al. [27] developed an ideal regression model to predict the performance of a liquid desiccant regenerator, which was applied in the case study to estimate potential energy savings and achieved consistent results with experiment. Besides this, the empirical models also appear in [7,28,29]. Essentially, they are fitted from experimental data under certain conditions. Hence, the model parameters may drift which will cause wrong model predictions. Wang et al. [30] proposed a static model based on the heat and mass transfer principles, where system information and fluid properties were lumped into seven parameters, which were estimated from experiment data. The model is efficient and agrees well with experiments, but it ignores system dynamics. In summary, the aforementioned models were proposed for various purposes. They are useful under specific requirements and conditions, and are rarely applicable to real-time control design.

In this paper, we focus on the liquid desiccant dehumidifier (LDD), a serial system of cooler and dehumidifier. The desiccant