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A hybrid dehumidifier model for real-time performance monitoring, control and optimization in liquid desiccant dehumidification system

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HIGHLIGHTS

- Study the heat and mass transfer process in dehumidifier for LDDS.
- A simplified yet accurate model for real-time performance optimization is developed.
- The model requires no iterative computations and is easy for engineering application.

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ABSTRACT

In this paper, a simplified, yet accurate hybrid model to predict the heat and mass transfer processes in a packed column liquid desiccant dehumidifier is developed. Starting from energy and mass balance principles, and by lumping the geometric parameters and fluids' thermodynamic coefficients as constants, the derived model only requires two equations together with total seven parameters for predicting the heat and mass transfer status in the dehumidifier. Commissioning information together with Levenberg–Marquardt method can be used to identify these parameters. Compared with the existing liquid desiccant dehumidification system dehumidifier models, the proposed model is very simple, accurate and does not require iterative computations. Experimental results demonstrate their effectiveness in predicting heat and transfer performances over a wide operating range. The model is expected to be applied in operational optimization, performance assessment, fault detection and diagnosis in liquid desiccant dehumidification system.

1. Introduction

In recent years, Liquid Desiccant Dehumidification System (LDDS) for air dehumidification has emerged as a viable alternative to conventional mechanical based dehumidification schemes where air is cooled below the dew point. The main advantages of the LDDS include: (1) possible energy savings by shifting the energy use away from electricity towards renewable or low grade energy, such as solar energy, geothermal energy, and waste energy from industrial processes [1]; (2) flexibility in operation to achieve independent temperature and humidity control; and (3) employ environment-friendly hygroscopic salt solutions as working fluids which do not contribute to ozone depletion [2].

The research on air dehumidification by LDDS may trace back to 1955 when Lof [3] first designed an open-cycle air-conditioning system using triethylene glycol as liquid desiccant. Since then, hundreds of research results have been published to refine the system in the areas of system design [4–6], experimental investigation [7,8] and performance analysis [9–11], where the fundamental heat and mass transfer processes were intensively investigated using finite difference, effectiveness NTU or empirical models [12].

Among the three modeling approaches, finite difference model has most frequently been used in investigation of LDDS performances for its accuracy. Factor and Grossman [13] and Gandhidasan et al. [14] developed theoretical models to test the columns to predict the performance of air dehumidification and solution regeneration under various operating conditions, and experiment results showed very good agreement with the theoretical model. Oberg and Goswami [15] presented a finite difference model and carried out detailed experimental investigations of heat and mass transfer inside the dehumidifier. Fumo and Goawami [16], Yin et al. [17] employed a modified Oberg and Goswami's model to study the LDDS with aqueous lithium chloride solution and random packing. Linear approximation was introduced to obtain analytical solution to the finite difference model and more accurate outlet conditions can be predicted by this method [18]. Mesquita et al. [19] developed a finite difference model for internally

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Nomenclature

A_a	convection heat transfer area of process air (m^2)
A_s	convection heat transfer area of desiccant solution (m^2)
b_1–b_4	constant (dimensionless)
c_1–c_3	parameters in heat transfer (dimensionless)
c_4–c_7	parameters in mass transfer (dimensionless)
c_p	specific heat of desiccant solution (J/(kg °C))
C	constant (dimensionless)
D	diameter of the structured packing (m)
D_a	diffusivity of process air (m^2/s)
D_{calc}	calculated data (dimensionless)
D_p	nominal size of packing material (m)
D_{real}	experimental data (dimensionless)
D_s	diffusivity of desiccant solution (m^2/s)
e	constant (dimensionless)
f	constant (dimensionless)
g	gravitational constant (m/s^2)
h	heat transfer coefficient (W/(m^2 °C))
h_a	heat transfer coefficient of process air convection (W/(m^2 °C))
h_s	heat transfer coefficient of desiccant solution convection (W/(m^2 °C))
H	Henry's law constant (Pa)
k	thermal conductivity (W/(m2 °C))
k_a	mass transfer coefficient of gas phase convection in the dehumidifier (kg/(m^2 s Pa))
k_s	mass transfer coefficient of liquid phase convection in the dehumidifier (kg/(m^2 s Pa))
K_G	overall mass transfer coefficient in the dehumidifier (kg/(m^2 s Pa))
$\dot{m}$	mass flow rate of fluid (kg/s)
$\dot{m}_a$	mass flow rate of process air (kg/s)
$\dot{m}_s$	mass flow rate of desiccant solution (kg/s)
N	mass transfer rate in the dehumidifier (kg/m^2 s)
$p_{a,in}$	water vapor pressure of inlet process air in the dehumidifier (Pa)
$p^*_{s,in}$	equilibrium water vapor pressure of inlet desiccant solution in the dehumidifier (Pa)
$P_{a,sat}$	saturated water vapor pressure (Pa)
Q	heat transfer rate in the dehumidifier (W)
R	ideal gas constant (J/(mol °C))
R_a	thermal resistance of process air convection (°C/W)
R_h	overall thermal resistance in the dehumidifier (°C/W)
R_s	thermal resistance of desiccant solution convection (°C/W)
$T_{a,in}$	temperature of inlet process air in the dehumidifier (°C)
$T_{s,in}$	temperature of inlet desiccant solution in the dehumidifier (°C)
V	volume flow rate of fluid (m^3/s)
α_t	specific surface area (m^2/m^3)
α_ω	wetted specific surface area (m^2/m^3)
μ	viscosity of fluid (Pa s)
μ_a	viscosity of process air (Pa s)
μ_s	viscosity of desiccant solution (Pa s)
ω_s	concentration of desiccant solution (%)
ϕ_a	relative humidity of process air (%)
ρ_a	density of process air (kg/m^3)
ρ_s	density of desiccant solution (kg/m^3)

Subscripts

a	process air
G	gas phase
in	inlet
out	outlet
s	desiccant solution
sat	saturated

cooled parallel plate liquid desiccant dehumidifiers. However, the process of developing and solving finite difference models are quite complex and iterative computation is absolutely necessary as the outlet conditions of desiccant solution are generally unknown, which makes the modeling approach unsuitable for real-time optimization and the performance estimation.

For the other two methods, Chen et al. [20] proposed NTU models in for a packed-type LDDS with two different flow configurations: parallel flow and counter flow. Compared with other models in literature, better accuracy can be obtained by using the proposed NTU model. Liu et al. [21] conducted a simulation of heat and mass transfer process with the corresponding data collected in a cross-flow dehumidifier and regenerator and a theoretical model with NTU input parameter was developed. Further, the authors showed that the analytical solutions of the available NTU model could be utilized in the optimization of the LDDS [22]. Khan and Ball [23,24] conducted sensitivity analysis for heat and mass transfer process of a packed-type liquid desiccant system to identify the performance of dehumidifier and regenerator through empirical method. Although the empirical methods are simple, some key parameters involving the performance of LDDS should be known in advance which may become very complicated in applications. Moreover, accuracy will decrease if the NTU or empirical model is expanded over a wider region.

In this paper, a simplified, yet accurate dehumidifier model to predict the heat and mass transfer processes for real-time performance monitoring, control and optimization in LDDS is developed based on the hybrid modeling approach [25–27]. Starting from energy and material balance principles, two simple non-linear equations can be obtained to present the heat and mass transfer process in dehumidifier. Through determining the process input–output variables and lumping dimensional parameters into seven characteristic parameters, Levenberg–Marquardt method can be applied to carry out the identification to the seven parameters by real-time experimental data. The proposed model need no iterative computation and is simple and accurate compared with the existing models. Experimental results show that the prediction errors are mostly fall within 10%, which validated the effectiveness of the modeling approach. Therefore, the model is expected to find its applications in real-time performance monitoring, control and optimization.

2. The operating principle of LDDS

A basic schematic diagram of Liquid Desiccant Dehumidification System (LDDS) operating with lithium chloride as desiccant is shown in Fig. 1, which is composed of two packing columns: dehumidifier and regenerator. The dehumidifier is to remove the moisture in the process air and the regenerator is to concentrate the diluted solutions from the dehumidifier to an acceptable concentration. The change of desiccant water vapor pressure in LDDS is illustrated in Fig. 2 and its working principle is briefly described below:

- In the dehumidifier, the strong desiccant solution is firstly cooled by the cooler until the state A is reached, and sprayed on top of the dehumidifier, directly contacting with process air, drawn from the bottom of the column by a fan, in a