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Hybrid model for heat recovery heat pipe system in Liquid Desiccant Dehumidification System

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HIGHLIGHTS

- A hybrid model for HPHE used for heat recovery in regenerator of LDDS is developed.
- The resulting model has only three unknown parameters that need to be identified.
- The proposed model is very accurate and does not require iterative computations.
- The model is easy for engineering application.

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ABSTRACT

In this paper, a hybrid model for heat pipe heat exchanger used for heat recovery in regenerator of Liquid Desiccant Dehumidification System (LDDS) is developed. The proposed hybrid model starts from the physical governing equations and lumps the complex geometric parameters and fluids' thermodynamic coefficients as constants since they have very small changes during the process operation. The resulting model has only three unknown parameters which can be determined by Levenberg-Marquardt method. Compared with the existing heat pipe models, the proposed model is very simple, accurate, and does not require iterative computations. A large amount of testing for the heat pipe heat exchanger installed in a pilot LDDS shows that the model is very effective to predict the performance in a wide operating range. The model is expected to find its applications in monitoring, control and optimization of the regenerator heat recovery process of LDDS.

1. Introduction

Liquid Desiccant Dehumidification System (LDDS) has been proposed as an alternative to the conventional mechanical based dehumidification system due to the following advantages: (1) energy consumption reduction by preventing dew point condition from occurring in order to remove the extra latent/humidity loads; (2) the potential ability of electricity replacement by using low-grade energy that increases the energy efficiency; and (3) the bacteria-killing function of the liquid desiccant solution that improves the indoor air quality and the health of occupants.

In LDDS, regenerator is indispensable for solution re-concentration and it consumes majority of energy in the whole system operation [1]. Many experimental and numerical investigations have been performed for regenerator optimization. In terms of structure design, internally heated regenerator [2,3], ultrasonic atomization regenerator [4], low-grade energy driven regenerator [5–7] and air-liquid flow configuration [8] have been explored by many researches. The performance of regeneration rate and regeneration thermal efficiency under different operating parameters of air and liquid desiccant has been analyzed [9–11]. For system modeling, hybrid heat and mass transfer model [12], simplified model [13] and finite difference model [14] have been developed to describe the regeneration process.

As a high efficient heat recovery device, heat pipe heat exchanger (HPHE) has been widely employed in air conditioning and conventional cooling based dehumidification systems [15–24]. All the studies show that heat recovery by HPHE is an excellent way for enhancing the energy efficiency in cooling based dehumidification systems. Three main approaches are frequently-used in the modeling of HPHE, i.e., the log-mean temperature difference model (LMTD), the effectiveness-number of transfer units ($\varepsilon - \mathrm{NTU}$) model and the finite difference model.

Feldman et al. [25] used LMTD model to analyze HPHE. In this study, the performance of horizontal HPHE was examined

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Nomenclature

b_s	parameters in heat transfer of HPHE (dimensionless)
b_e	parameters in heat transfer of evaporator section (dimensionless)
b_c	parameters in heat transfer of condenser section (dimensionless)
C	constant (dimensionless)
C_p	specific heat of flowing air (J/kg °C)
D	diameter of one heat pipe (m)
D_{real}	experimental data (dimensionless)
D_{calc}	calculated data (dimensionless)
f	constant (dimensionless)
g	constant (dimensionless)
K	thermal conductivity [W/(m^2 °C)]
$\dot{m}$	mass flow rate of air (kg/s)
n	number of heat pipe row (dimensionless)
NTU_e	number of transfer units of evaporator section of HPHE
NTU_c	number of transfer units of condensor section of HPHE
Nu	Nusselt number (dimensionless)
Pr	Prandlt number (dimensionless)
Q	actual heat transfer rate in HPHE (W)
$Q_{\max}$	maximum heat transfer rate in HPHE (W)
Re	Reynolds number (dimensionless)
S	convection heat transfer area (m^2)
S_e	convection heat transfer area of evaporator section of HPHE (m^2)
S_c	convection heat transfer area of condenser section of HPHE (m^2)
$T_{e,in}$	temperature of warm regenerating air (°C)
$T_{e,out}$	temperature of exhausting regenerating air (°C)
$T_{c,in}$	temperature of ambient air (°C)
$T_{c,out}$	temperature of preheated regenerating air (°C)
U	heat transfer coefficient [W/(m^2 · °C)]
U_e	heat transfer coefficient of hot air [W/(m^2 · °C)]
U_c	heat transfer coefficient of cool air [W/(m^2 °C)]
V	volume flow rate of air (m^3/s)
ε	thermal effectiveness of HPHE
ε_e	thermal effectiveness of evaporator section
ε_c	thermal effectiveness of condenser section
$\varepsilon_{\min}$	lower thermal effectiveness
$\varepsilon_{\max}$	higher thermal effectiveness
ε_p	thermal effectiveness for an individual heat pipe
μ	viscosity of air (Pa s)
ρ	density of air (kg/m^3)
υ	velocity of air (m/s)

Subscripts

e	evaporator section of HPHE
c	condenser section of HPHE
in	inlet
out	outlet

including the temperature drop due to the vapour flow inside the heat pipes. They found that using staggered tube bundles, larger diameter of heat pipes, smaller fin heights and more fins number could improve the performance of HPHE. Wakiyama et al. [26] developed a LMTD model for an air-to-air HPHE. This study covered both horizontal and vertical operation of HPHE and had a good consistency with the experimental data. An important parameter in $\varepsilon - \mathrm{NTU}$ model is heat exchanger effectiveness. It is the ratio of the actual to the maximum heat transfer rate. Tan and Liu [27] used this model to study an air-to-air HPHE by neglecting the internal resistance of heat pipe. The results had a good agreement with Ref. [29]. It was concluded that decreasing heat capacity ratio would increase the effectiveness of HPHE since more heat could be transferred to the low-temperature fluid. Soylemez [28] proposed a simple algebraic formula using $\varepsilon - \mathrm{NTU}$ method for HPHE. With this model, the optimal HPHE effectiveness, optimal heat recovery net savings and payback period could be determined. Finite difference has been the most frequently-used model in the investigation of HPHE in recent years. Huang et al. [29] developed finite difference equations to calculate the thermal performance of HPHE. The results were validated experimentally. Jung et al. [30] proposed a row-by-row heat transfer model which was useful for understanding the temperature distribution of each row and could be used to predict the cold-side inlet temperature of HPHE with counter flow. Han et al. [31] established finite difference heat transfer model of HPHE starting from $\varepsilon - \mathrm{NTU}$ model. This model was employed to compute the heat flow of each row of heat pipe. Hughes et al. [32] investigated ventilation streams in buildings and utilized heat pipe technology to recovery energy. Analytical model were developed from HPHE model and CFD simulation was conducted to predict the heat recovery rate. Based on the literature review, it is found that these three modeling approaches are accurate enough for the analysis of HPHE. However, for LMTD and finite difference model, iterative computation procedure is required. The deriving and resolving processes are very complicated. For $\varepsilon - \mathrm{NTU}$ model, the heat transfer coefficient is usually very hard to calculate. Some key parameters of fluid and structured must be known in advance. The characteristics of these three modeling approaches make them unsuitable for the performance estimation, real-time control and optimization of HPHE heat recovery process in regenerator.

This paper studied the heat recovery process of regenerator in the LDDS. In order to monitor, control and predict the heat recovery process, a simple hybrid model [12,33,34] is proposed. The proposed hybrid model starts from the physical governing equations and lumps the complex geometric parameters and fluids' thermodynamic coefficients as constants since they have very small changes during the process operation. The resulting nonlinear equations only have three unknown parameters. They can be identified by Levenberg-Marquardt method [35–37], which is the most common method for nonlinear least-squares minimization [38]. The hybrid model needs no iterative computation and is simpler than existing models. Experimental validation shows that the relative errors between the experimental data and the model prediction results are mostly within $\pm 10\%$, which indicates the accuracy and effectiveness of the proposed model. This model is expected to be employed in monitoring, control and optimizing the heat recovery process of regenerator in LDDS.

2. Working principle of regenerator with heat recovery

A schematic diagram of regenerator with heat recovery in LDDS operating with lithium chloride is shown in Fig. 1. It mainly consists of four components: regenerator tower, structured packing, heat exchanger and HPHE.

The HPHE is composed of a group heat pipes and the central part is partitioned to divide the HPHE into evaporator section and condenser section. The system operating procedure is briefly described below: