International Journal of Thermal Sciences 131 (2018) 1–13

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

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

A novel finite difference model coupled with recursive algorithm for analyzing heat and mass transfer processes in a cross flow dehumidifier/regenerator

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ARTICLE INFO

Keywords:
Coupled heat and mass transfer
Dehumidification
Liquid desiccant
Finite difference model
Recursive algorithm

ABSTRACT

Maintaining the relative humidity within the desired level in hospitals, research laboratories and pharmaceutical industries is very crucial. Among the various techniques reported over the last three decades, liquid desiccant dehumidification has been found promising. Dehumidifier and regenerator are the key components in the liquid desiccant dehumidification system. In this paper, the coupled heat and mass transfer analyses in a cross flow liquid desiccant dehumidifier and regenerator are presented. A novel finite difference based thermodynamic model is developed using the governing equations of mass, momentum and energy and a recursive algorithm is proposed for solving the developed model. The simulated results obtained from the developed model are validated with the experimental data reported in the literature and a good agreement is observed between them. The contour plots for the distribution of air and desiccant enthalpies, air specific humidity and solution concentration along the longitudinal and the transverse directions of the packed tower are represented. Also, the contour plots for the desiccant concentration at different Lewis numbers are presented. Further, the influence of Lewis number on operating and performance parameters are also discussed in detail.

1. Introduction

Conventional air conditioning system dehumidify the air by cooling it below the dew point temperature and re-heating it to the desired temperature. This type of dehumidification process consumes more power. To overcome this issue, desiccant based dehumidification system has been introduced [1–3]. Desiccant based dehumidification system is classified as solid desiccant based dehumidification system and liquid desiccant based dehumidification system. Compared to solid desiccant based dehumidification system, liquid desiccant based dehumidification system is advantageous due to less air side pressure drop, less maintenance, operational flexibility and utilization of low-grade thermal energy sources such as solar or waste heat for the regeneration of liquid desiccant. They can be employed in large capacity industrial deep drying applications [4]. Therefore, liquid desiccant based dehumidification system is chosen for the present analysis. The main components of this system are dehumidifier and regenerator.

In dehumidifier/regenerator, desiccant solution enters into a packed column where it exchanges heat and mass with the air that enters into the packed column in a cross flow direction. In a dehumidifier, the cool and strong solution interacts with the process air and moisture transfer takes place from air to liquid desiccant due to vapour pressure difference. During this interaction, heat is released due to exothermic reaction and condensation process. Thus, the solution gets heated and diluted. In a regenerator, when the air interacts with the diluted and hot desiccant solution, desorption of water vapor takes place from the liquid desiccant to the air due to vapour pressure difference. During this interaction, heat is released due to exothermic reaction and evaporation process. Thus, the solution gets cooled and concentrated (conversion of weak solution to strong solution).

Several researchers have investigated the performance of the liquid desiccant dehumidifier/regenerator employing numerical models [3–7] [9–14], [16–18] [24], and performing experimental studies [2,5–8], [15, 19–23]. The estimation of air and desiccant property variations along the length and height of the dehumidifier and the regenerator are complicated. Thus, a numerical tool, is generally used to predict these variations. As listed in Table 1, very few models were developed for predicting the variations of air and desiccant properties and also for predicting the heat and mass transfer characteristics along the cross – flow liquid desiccant dehumidifier and the regenerator. Only Li et al. [5] reported the variations of air and desiccant properties along the liquid desiccant regenerator. Further, the models reported in the

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https://doi.org/10.1016/j.ijthermalsci.2018.05.029
Received 5 November 2017; Received in revised form 30 January 2018; Accepted 17 May 2018
1290-0729/

Nomenclature

a	specific area of the packed tower (m^2/m^3)
$c_{p,m}$	specific heat of humid air (kJ/kg K)
G	mass flux (kg/m^2s)
H	height of the packed tower (m)
h	enthalpy (kJ/kg)
L^*	effective length of the packed tower (m)
Le	Lewis number
T	Temperature(°C)
w	width of the packed tower (m)
X	concentration of the desiccant solution (%)

Greek Letters

ξ_T	thermal effectiveness (%)
ξ_m	moisture effectiveness (%)
ω	specific humidity of humid air (kg_v/kg_{da})
α_h	coefficient of heat transfer (W/m^2 K)
α_m	coefficient of mass transfer (kg/m^2 s)
δ	latent heat of evaporation (kJ/kg)

Subscripts

a	Air
s	desiccant solution
h	heat transfer
m	mass transfer
e	Equilibrium

Super scripts

i	Inlet
o	Outlet
avg	Average

Table 1
Previous models on heat and mass transfer processes along the dehumidifier/regenerator.

Author	Component	Type of flow	Nature of analysis
Das and Jain [6]	Dehumidifier	Cross	Influence of different types of flat plate membrane contactors on performance characteristics of dehumidifier are analyzed.
Liu et al. [5]	Dehumidifier and regenerator	Cross	Studied the air and desiccant parameters numerically by taking constant Lewis number (Le = 1).
Khin et al. [8]	Dehumidifier	Cross	Performance characteristics of the dehumidifier are studied using air to air heat and mass transfer processes.

literature, generally require numerous simulation procedure for solving the governing equations and also complicated. Moreover, the major challenges faced by several researchers are the estimation of heat and mass transfer coefficients or Lewis number [2,5,19–22]. In addition, the reported models were used for predicting either the performance of the liquid desiccant dehumidifier or the performance of the liquid desiccant regenerator [6–8] [12,16–18], [22].

Therefore, this paper focuses on proposing a simplified thermodynamic approach for analyzing the performance of a cross – flow liquid desiccant dehumidifier as well as a liquid desiccant regenerator using two developed correlations for predicting the heat and mass transfer coefficients in terms of thermal effectiveness and moisture effectiveness. A finite difference method is implemented for solving the developed thermodynamic model using a recursive algorithm. Using the developed model, the variations of air and desiccant enthalpies, concentration of desiccant and air specific humidity along the packed tower (dehumidifier/regenerator) are presented. In addition, Lewis number is formulated in terms of thermal and moisture effectiveness and studied the influence of Lewis number on operating and performance parameters of the packed tower.

2. Thermodynamic model

Fig. 1 shows the schematic of adiabatic cross flow packed tower (dehumidifier/regenerator). In both the dehumidifier and the regenerator, the air and the desiccant solution flow in longitudinal and transverse directions, respectively. As shown in Fig. 1, the length, height and width of the packed tower are taken along x, y and z directions, respectively. The heat and mass transfer processes are uniform along the z direction of the packed tower. So, the transfer processes between the air and the desiccant remains same in any x – y plane along the z – direction. Therefore, in the present study, transfer processes in x – y plane at particular z – coordinate is chosen for deriving the governing equations (Fig. 2).

The assumptions considered for deriving the governing equations are.

- Working fluids are Newtonian.
- Velocities of working fluids are uniform along the longitudinal and transverse direction.
- No heat dissipation to the surroundings.
- Local heat and mass transfer coefficients doesn't vary during the transfer processes.
- Heat conduction and molecular diffusion among the liquid desiccant and air are negligible along the flow direction [6,20].

2.1. Governing equations

The energy balance for the air side flow is given by

$$G_a\frac{\partial h_a}{\partial x} - G_a\delta\frac{\partial \omega_a}{\partial x} + \alpha_h a(T_a - T_s) = 0 \tag{1}$$

where $\delta\frac{\partial \omega_a}{\partial x}$ and $\alpha_h a(T_a - T_s)$ are the latent heat generated during

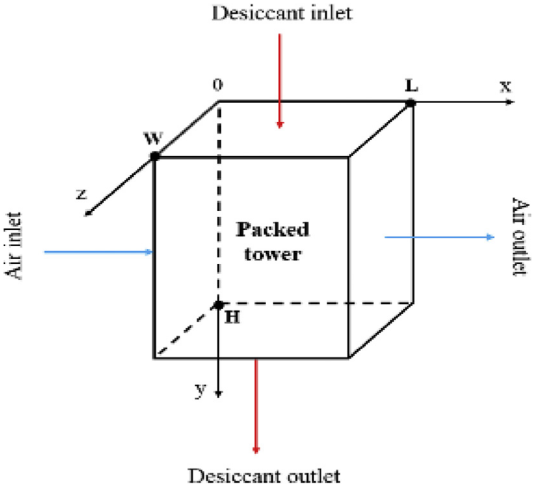

Fig. 1. Schematic of the cross flow packed tower.