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Model development of heat/mass transfer for internally cooled dehumidifier concerning liquid film shrinkage shape and contact angles

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A B S T R A C T

Moisture affects building materials, the thermal comfort of building occupants and the work performed by them. The plate liquid desiccant air-conditioning system (LDACS) is a promising dehumidification alternative to traditional air-conditioning system for lower energy consumption and less pollution. The shrinkage of the falling film on working plates critically influences the dehumidification performance by affecting the wetting area and film thickness. This paper developed a new model of plate dehumidifier concerning the shrinkage shape and the variable film thickness of falling film. The new model was validated by experiments and compared with existing models. The results indicated that the effect of contact angles on dehumidification performance can be accurately predicted. The moisture removal rates increased rapidly from 2.0 g/kg to 2.56 g/kg as the contact angles decreased from 85° to 5°, while the wetting area increased from 0.145 m^2 to 0.176 m^2. The distribution of the humidity ratio of process air along flow direction with different contact angles was also simulated. Besides, the average film thickness decreased from 0.952 mm to 0.889 mm as the contact angles decreased from 85° to 5°. The annual electricity consumption of plate LDACS with different contact angles for a typical building in Hong Kong was estimated and analysed by using the newly developed model. The new model can achieve a better predictive accuracy by considering the exact shrinkage shape of falling film and the findings can provide a new insights improving the performance of plate dehumidifiers and other industrial applications, such as vertical condensers, evaporators and absorption towers.

1. Introduction

Liquid desiccant air-conditioning systems (LDACS) have drawn increasing attentions as possible alternative to the traditional vapour-compression refrigeration systems which have the limitations of high energy consumption, poor humidity control and low indoor air quality [1]. By handling the extra humidity with liquid desiccant absorption, the LDACS are energy-efficient and environment-friendly, especially in hot and humid regions. Furthermore, low-grade energy, such as solar energy or industrial waste energy, can be used in the regenerators of LDACS [2], which helps further reduce the system energy consumption. In principle, the hybrid system combining liquid desiccant units and traditional vapour-compression chilling units can achieve a marked increase in the coefficient of performance (COP) [3,4].

LDACS with packing dehumidifiers/regenerators are widely used and featured by large contact area between the liquid desiccant and the process air [5–10]. However, there occurs some problems, such as high air pressure loss and carryover of desiccant droplets. Droplet carryover can cause the corrosion of the ventilation system and the potential pollution of indoor air [11]. Plate LDACS with internally cooled/heated units are developed to solve these two problems. The latent heat released during the absorption process is removed simultaneously by the internally-cooled unit to avoid temperature increase of liquid desiccant. Therefore, a relatively low surface vapour pressure can be maintained, which facilitates the mass transfer between liquid desiccant and process air [12]. Many researchers investigated the heat and mass transfer performance of plate LDACS [13–18]. Zhang et al. [19] analysed the operating performance of an internally-cooled dehumidifier experimentally and theoretically. Yin et al. [20] investigated the internally cooled/heated dehumidifier/regenerator of liquid

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Nomenclature

A	Wetting area, m^2
CA	Contact angle, °
C_p	Specific heat, kJ/(kg·K)
d	Width of the air channel, m
D	Width of the rim part, m
h	Enthalpy, kJ/kg
h_c	Heat transfer coefficient between air and desiccant, W/(kg·K)
h_d	Mass transfer coefficient, kg/(m^2·s)
h_f	Heat transfer coefficient between cooling water and desiccant, W /(kg·K)
H	Height, m
k	Mass diffusion coefficient, m^2/s
L	Length, m
Le	Lewis number
m	Mass flow rate, kg/s
n	Element number
P_0	Base value
Δp	Variation
Re	Reynolds number
Sc	Schmidt number
SC	Sensitivity coefficient
T	Temperature, °C
V	Velocity, m/s
W	Width, m
Δx	Shrinkage distance, m
X	Concentration, %
α	Contact angle, °
β	Shrinkage angle, °
γ	Latent heat, kJ/kg
ω	Humidity ratio, g/kg
$\Delta\omega$	Moisture removal rate, g/kg
σ	Surface tension, N/m
ε	Deformation factor
ρ	Density, kg/m^3
δ	Film thickness, mm
μ	Dynamic viscosity, Pa·s

Subscripts

ave	Average
cen	Central part
f	Cooling water
g, G	Air
L	Liquid solution
m	Maximum
rim	Rim part
s	Solution
S	Solid
Sat	Saturation status
v	Vapour
x	x coordinate
y	y coordinate
z	z coordinate

desiccant systems experimentally, and found that the regeneration efficiency of internally heated regeneration was much higher than that of the adiabatic one. In addition, several simulation models including the finite differential model [21,22], effectiveness-NTU model [23] and various simplified models [24], are available to predict the heat and mass transfer performance of LDACS. Niu [25] developed a two dimensional (2-D) model based on the finite differential model to investigate the performance of dehumidifiers, in which the mass transfer coefficient was obtained from experiments. Moreover, Ren [23] proposed corrections to the simple effectiveness-NTU method for counter-flow cooling towers. Liu et al. [26] developed a simplified method using enthalpy effectiveness and moisture effectiveness as indexes to predict dehumidifier performance. Three types of models for internally cooled/heated dehumidifier/regenerator were summarized by Luo et al. [16], i.e., models not considering the liquid film thickness, models considering uniform liquid film thickness and models considering variable liquid film thickness.

The wetting area of the liquid desiccant is a critical factor affecting the dehumidification performance of LDACS [27]. Many researchers have investigated the uncomplete wetting characteristics of falling film [28,29]. Peng and Howell [30] theoretically investigated the incomplete surface wetting conditions in desiccant air conditioners. Jain et al. [31] subsequently proposed two wetness factors to investigate the influence of incomplete wetting on heat and mass transfer performance. Zhang et al. [32] experimentally investigated the shrinkage characteristics of heated falling film over a vertical stainless steel plate, and observed a pronounced contraction of the falling film along the flow direction caused by Marangoni effect.

Generally, the incomplete wetting characteristics, especially the exact shrinkage shape of the falling film, have not been taken into consideration in most of the simulation models. In addition, the variation of the falling film thickness along the flow direction has seldom been considered. In this paper, a new model of internally cooled dehumidifier considering the falling film shape and variable film thickness with different contact angles was developed to estimate the dehumidification performance. As the contact angle of the liquid on the working surface can significantly affect the wetting area of falling film [33], a comparative experimental setup of plate dehumidifiers with different working plates was also conducted. The new model was validated by the experimental results and compared with the existing models. The effect of contact angles on dehumidification performance as well as wetting area and falling film thickness was investigated theoretically. Then the effect of the desiccant solution temperature and cooling water temperature on the wetting area with different contact angles was also investigated. Lastly, the annual electricity consumption of plate LDACS with different contact angles for a typical commercial building in Hong Kong was estimated and analysed using the newly developed model.

2. Methodology

In this paper, both experimental and simulation studies were carried out to investigate the wetting area and heat/mass transfer performance of plate dehumidifiers with different surface contact angles.

2.1. Model development of falling film shrinkage with different contact angles

According to Zhang et al. [32] and our previous research [33], the falling film shrinks rapidly along the flow direction and the shrinkage varies considerably depending on the contact angles of the desiccant solution on working surface. In this study, the model