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Technical Note

Model development for the wetted area of falling film liquid desiccant air-conditioning system

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ABSTRACT

The film wetted area is a significant parameter affecting the heat and mass transfer of falling film liquid desiccant air-conditioning system. In this paper, a theoretical model with the analytical solution was developed for calculating the wetted area accurately, by solving the desiccant interface concentration and temperature gradients. Comparing with the experimental data on a single channel internally heated regenerator, the results with the new model showed better agreement than those of the previous model. The average error reduced significantly from 16.4% to 4.8% for the experiments with different solution temperatures, and decreased from 10.8% to 7.0% for those with different plate surface temperatures. With this new model, decreasing the film thickness and contact angle could significantly increase the film area, and the area also increased with the air and extra fluid temperature. This research is useful to help to predict the wetted area accurately and to increase the area for improving system efficiency of liquid desiccant air-conditioning system and other falling film applications.

1. Introduction

Traditional air dehumidification technology has many problems. By handling the extra humidity with desiccant absorption, the liquid desiccant air-conditioning system (LDAC) has been regarded as a promising alternative. The dehumidifier and regenerator are the most critical components which determine the heat and mass transfer. To avoid the corrosion of ventilation system and pollution of indoor air, falling film is an effective type to feed in desiccant due to its low pressure drop and low possibility of droplets carried by air [1]. Falling film could also be applied in novel LDACs such as membrane-based and plate-fin-based systems [2,3]. With the extra cooling/heating fluid behind the working surface, the internally heated/cooled LDAC could maintain the surface vapor pressure of desiccant, and miniaturize the system dimensions.

In previous studies, the working surface is usually wetted incompletely by solution film in practical systems, and the actual area is difficult to be predicted [4,5]. The enlargement of wetted area could effectively enhance the heat and mass transfer across the air/liquid interface [6]. Recently, Qi et al. [7] developed a model to predict the area of internally heated regeneration, but the impact of solution concentration was neglected. The film area was also concerned in many other applications. For the water film, Zhang et al. [8] developed a model to predict the contraction distance, considering the uneven surface tension in the transverse direction.

The study of literature indicates that previous research on the predication of film wetted area of liquid desiccant system is limited and insufficient. In this paper, a theoretical model with the analytical solution was built, by considering the effects of desiccant concentration and temperature gradients on the film interface, and the parameters of desiccant, air and extra fluid. To verify the model, experiments were conducted with a single channel internally heated regenerator.

2. Model development

The typical liquid falling film is symmetrical, and includes two parts: the central part with almost uniform solution temperature and the rim part with the dramatic changed temperature [6]. The main reason causing the film deformation is the difference of surface tensions between the sides of rim part, namely the Marangoni effect, which leads to a desiccant flow in the transverse direction. Fig. 1 shows a diagram of the liquid desiccant falling film.

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Nomenclature

A	area m^2
h	convection heat transfer coefficient between solution and air kW/(m^2 °C)
c	specific heat capacity kJ/(kg °C)
D	width of rim part m
$\overline{R_w}$	dimensionless wetted width of falling film
$\dot{m}$	mass flow rate kg/s
a	thermal diffusivity m^2/s
t	temperature °C
u	flow velocity m/s
λ	thermal conductivity kW/(m °C)
W	width m
Δx	deformation distance of solution film in the transvers direction m
δ	thickness of solution film m
μ	dynamic viscosity Pa s
ε	deformation indicator of solution film
ρ	density kg/m^3
θ	contact angle °
σ	surface tension N/m
ζ	solution concentration
ω	moisture content kg/kg

Subscripts

a	air
p	plate
in	inlet
i	initial
cen	central part
s	solution
out	outlet
w	wetting
rim	rim part

As the integrand increases monotonically, the function of film deformation distance [7] could be solved with the mean value theorem of integrals, as shown in Eq. (1). So, the film wetted area could be calculated in Eq. (2).

$$\Delta x \approx \sqrt{2}u_{y,m}\frac{|\sigma_{rim}-\sigma_{cen}|}{\sigma_{rim}-\sigma_{cen}}f\left(\frac{y}{2}\right)y \quad \text{where } f(y) = \left[\left(1+\frac{\delta(y)^2(\sigma_{cen}-\sigma_{rim})^2}{4u_{y,m}^2\mu^2D_r^2}\right)^{1/2}-1\right]^{1/2} \tag{1}$$

$$A_w = \int_0^y (W_i - \Delta x)dy \tag{2}$$

where σ stands for the solution surface tension, and θ refers to the solution contact angle on a specific working surface. δ is the film thickness, which changes along the flow direction due to the change of film width [7].

To solve the equations, the solution surface tension, σ_{cen} and σ_{rim}, should be derived firstly. σ_{cen} is decided by the interface concentration and temperature in the central side, $\zeta_{s,z=\delta(y)}$ and $t_{s,z=\delta(y)}$, and σ_{rim} is the function of the solution concentration and the working surface temperature at the film edge, $\zeta_{s,p}$ and t_p.

To obtain the interface concentration, the Whitman's Two-film theory was applied [9]. Thin boundary films, which provide the main resistances of mass transfer, are assumed to exist on both sides of air and liquid on their interface, and stagnant with a fixed thickness. The schematic diagram of mass transfer is shown in Fig. 2.

Therefore, governing equations and boundary conditions for $\zeta_{s,z=\delta_{cen}}$ is as follows:

$$\begin{array}{ll} & z=0 \quad u_y=0 \\ \mu\frac{\partial^2 u_y}{\partial z^2}+\rho g=0 & z=\delta-\delta_{sf} \quad \zeta_s=\zeta_{s,\infty}; \\ u_y\frac{\partial \zeta_s}{\partial y}=D_s\frac{\partial^2\zeta_s}{\partial z^2} & z=\delta \quad \frac{\partial u_y}{\partial z}=0; \quad t_a=t_s; \quad D_s\frac{\partial \zeta_s}{\partial z}=-k_s(\zeta_s-\zeta_{a,i}); \\ & y=0 \quad \zeta(x,0,z)=\zeta_{s,in}; \end{array} \tag{3}$$

where $\zeta_{s,\infty}$ is the concentration of the bulk solution phase. $\zeta_{a,i}$ means the equivalent concentration of air on the interface, which is the function of air temperature and moisture content. k_s is the convection mass transfer coefficient between air and solution. δ_{sf} means the thickness of assumed thin boundary film on the desiccant side, $\delta_{sf}=\frac{D_s}{k_s}\delta$.

Solving the above equations, the solution interface concentration of both sides of the rim part could be calculated, with the following assumptions: (a) at the central side, the air interface

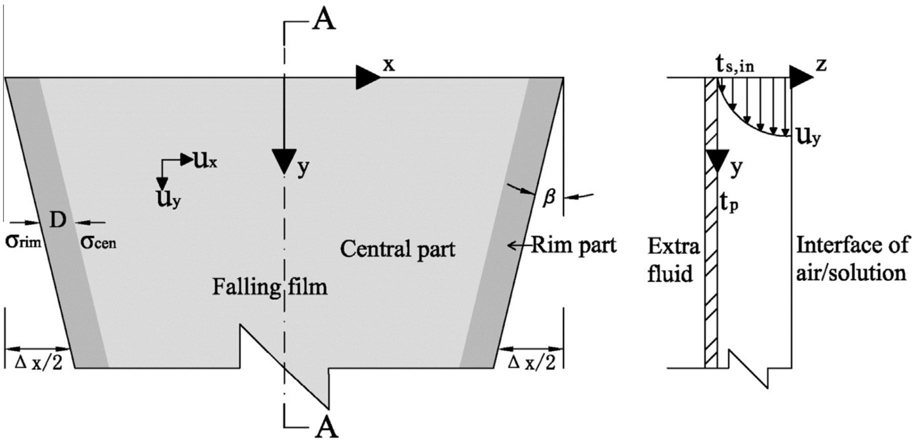

Fig. 1. Schematic of solution falling film and the y–z cross section.