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Investigation on the liquid contact angle and its influence for liquid desiccant dehumidification system

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ABSTRACT

The liquid desiccant dehumidification system (LDDS) is promising by removing extra air moisture effectively with absorption. By significantly affecting the film wetted area, the desiccant contact angle of the liquid/air interface on the working plate is critical for the system performance. Its value accuracy also seriously impacts the prediction accuracy of theoretical models. However, previous research on the liquid desiccant contact angle was limited, and the results of current predictions were questionable. This paper tested the contact angle of commonly used desiccants, Lithium Chloride (LiCl) and Lithium Bromide (LiBr) aqueous solution, on the stainless steel plate, and developed empirical formulas for predicting the angle. For both desiccants, the contact angle increased with the solution mass concentration and decreased with temperature. With the increase of plate surface roughness, the angle first increased and then decreased. These parameters showed much obvious effects on the angle of LiCl. For the effect of roughness, the maximum changing rate of LiCl was 0.13°/nm compared with 0.07°/nm of LiBr. Errors between new formulas and experiment ones were acceptable, showing an average absolute error of 12.3% for LiCl and 9.4% for LiBr. Furthermore, the effects of contact angle on the film wetted area were investigated experimentally with a single channel regenerator. When the plate surface was hydrophilic, the initial film width was significantly enlarged, with a rate of -2.0×10^{-3} m per degree, and film contraction along the flow direction was restrained due to the small contact angle. So, the film wetted area increased with an average changing rate of -9.7×10^{-4} m^2 per degree, and the mass transfer was effectively enhanced by 2–3 times. Effective measures to reduce the contact angle were also proposed.

1. Introduction

The traditional dehumidification technology of air-conditioning (AC) system in buildings has many limitations in handling the indoor humidity [1–3], which may be more severe in humid regions. The desiccant dehumidification with liquid or solid materials is considered as a promising alternative by dealing with the extra humidity with absorption [4–6]. It could also reduce the energy consumption of combined refrigeration system [7]. Due to its lower regeneration temperature, the liquid desiccant dehumidification system (LDDS) has drawn increasing attentions, as it is suitable to cooperate with solar or waste energy applications. Dehumidifier and regenerator are the critical components of LDDS, which determine the system efficiency and heat/mass transfer performance. To avoid the corrosion of ventilation system and potential pollution of indoor air, the falling film dehumidifier/regenerator is suitable for air/desiccant contacting due to its low possibility of droplets carried by the air [8].

For evaluating the heat and mass performance of LDDS system, the film area of desiccant is a critical parameter [9]. In practical falling film systems, the uncompleted wetting condition has been reported in many previous researches [10–14]. Zhang et al. [15,16] developed a theoretical model to evaluate the water film area, and indicated that the contact angle of water on the working surface was indispensable for calculating the area. Recently, Qi et al. [17] developed a theoretical model for calculating film deformation during the liquid desiccant regeneration, and found that small contact angle may benefit the film wetted area. In their studies, the values of contact angle were usually obtained empirically with the equation developed by Al-Farayedhi et al. [18] or the studies by Luo et al. [19]. But, these calculation methods may not be suitable for the contact angle of desiccants used in LDDS system, and the results were questionable compared with the

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Nomenclature

A	area (m^2)
e	relative measurement error (%)
$\dot{m}$	mass flow rate (kg/s)
Ra	profile roughness parameter (nm)
$\overline{R_w}$	dimensionless wetted width of falling film (–)
t	temperature (°C)
W	width (m)
α	contact angle (°)
δ	thickness of solution film (m)
σ	surface tension (N/m)
ω	moisture content (kg/kg)
ζ	solution concentration (-)
Δx	deformation distance of solution film in the transverse direction (m)

Subscripts

a	air
i	initial
in	inlet
out	outlet
s	solution
w	wetting

experimental ones. Most studies on the measurement of liquid contact angle concerned the pure water or organic solutions [20,21]. The contact angle in this paper means the contact angle of liquid desiccant on the solid working surface, which the value indicated the spreading condition of liquid on the solid surface.

It is summarized that the desiccant contact angle showed an important effect on system performance by influencing the film wetted area. As the angle is an indispensable parameter in theoretical models, its value accuracy seriously impacts the simulation accuracy of wetted area and the heat/mass transfer efficiency accordingly. In this paper, to predict the accurate value of contact angle, several influencing parameters of the angle of commonly used desiccants, LiCl and LiBr, were investigated experimentally. The semi-empiric equations for predicting the angle were developed and compared with the test data. Furthermore, by designing and testing a single channel liquid desiccant system, the effects of contact angle on the film wetted area and mass transfer performance were investigated and analyzed. The test plates were made of stainless steel SUS316 due to its good anti-corrosion performance. As falling liquid film is widely employed in many industrial applications, such as vertical condensers, film evaporators and absorption towers, our results could be also applied for their performance improvement.

2. Methodology

2.1. Test rig for contact angle of desiccant solution

Three influencing factors of contact angle of LiCl and LiBr solution were investigated, including the temperature and mass concentration of desiccant solution, and the roughness of the test plate. The solution was prepared with the anhydrous LiCl or LiBr powder ($\geqslant$99.5%) and deionized water, and sealed in the container to avoid the mass transfer with the surrounding air. Four plates made by SUS316, with the size of $20 \times 20 \times 5$ mm, were produced with different surface roughness. According to the common operation conditions of LDDS, the solution concentration was ranged from 25–40%. The temperature of test plate was controlled from 25–55 °C with the resistance heater by changing the supplied voltage. As the solution droplet during the test was small, its temperature was assumed same with the plate surface temperature at that point. This assumption is suitable for falling film LDDS, as the contact angle was observed at the film edge where film thickness was very thin.

The contact angle was measured with the sessile drop method by using the contact angle goniometer with a maximum error was 0.05°. The liquid droplet was deposited by a syringe pointed vertically down onto the sample, and the angle could be captured by a high resolution camera and analyzed by analysis software. The liquid wets the surface well if the contact angle is less than 90°, while the surface is insufficiently wetted if contact angle is greater than 90°.

The local temperature of droplet was measured by the thermal camera imager, with a maximum error of 0.1 °C. The profile roughness parameter, Ra, was observed by the laser optical interferometer with accuracy of 0.01 nm. Ra values of four test plates were 393.8, 287.4, 147.4 and 82.7 nm respectively. The samples were well-processed with a unique surface roughness to avoid the asymmetric condition of the apparent contact angle. The types of thermal camera, contact angle goniometer and laser optical interferometer are Fluke Ti20, MD200 and WYKO NT8000, respectively. The photos of devices used in this experiment were shown in Fig. 1.

To measure the contact angle, the sessile drop test method was applied by placing a liquid droplet with a syringe vertically and moving the plates up to let the droplet down onto the sample. The size of every drop was 5 μL. After 30 to 60 s to reach the steady state, the supporting software of the goniometer could identify and record the angle automatically. The measured contact angles for 4–5 times would be averaged to improve the test accuracy. The test was conducted in a thermostatic room with the temperature of 24.5 ± 1 °C. With the test data under different conditions, equations of contact angle could be obtained by the multiple linear regression, and the calculation results were compared with the test data for validation.

2.2. Test rig for the impact of contact angle on the wetted area

To investigate the effects of contact angle on the wetted area, experiments with a single channel liquid desiccant system were conducted. During the experiment, the solution film was distributed on the vertical working surface and exchanged the heat and moisture with countercurrent air by direct contact. Two kinds of working surfaces, indicated as S1 and S2, were applied. Both surfaces were made of stainless steel SUS316 with the average Ra of 608 nm. For S1, the whole surface was cleaned with the water and alcohol, and then carefully blown with the hot air, to make the whole surface as dry as possible. In terms of S2, the surface was coated with the commercially available TiO_2 hydrophilic coating on which the surface contact angle could be effectively reduced. LiCl aqueous solution was selected as desiccant. The schematic of the test rig and the working surface are shown in Fig. 2.

A thermal camera imager was applied for obtaining the film wetted area and desiccant surface temperature of falling film. The main measurement devices and errors were summarized in Table 1. As the test rig was remodeled based on the rig built in our previous research, the details and measurement methods could be found in Refs. [17,22]. Due to its larger change range of operation temperature, the regeneration process was conducted.