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Experimental investigation of the wetting characteristics of an aqueous ionic liquid solution on an aluminum fin-tube substrate

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ABSTRACT

In falling film liquid desiccant systems, finding a suitable pair of liquid desiccant and contact surface is of primary engineering interest. This requires knowledge on the wetting characteristics of the liquid on the solid substrate, which consequently requires intensive experimental investigation. In this study, the wetting characteristics of a new ionic liquid aqueous solution in an aluminum fin-tube substrate were experimentally investigated. Then, a simple method for estimating the wetted area on the substrate through image processing was developed. Visual analysis of the surface wetting was also conducted, and three types of wetting patterns are discussed. Experimental results on the static contact angle and contact angle hysteresis suggest that the ionic liquid solution is mostly wetting, and the aluminum surface is slightly to moderately rough. It was found that the wettability of the ionic liquid solution increases as the ionic liquid mass fraction increases. The wetting hysteresis phenomenon and the factors contributing to its occurrence were also clarified. The results from this study would be useful for the development of a new model or improvement of existing wetting models, which can help improve the prediction and control of the heat and mass transfer performance in internally cooled/heated fin-tube contactors.

Étude expérimentale des caractéristiques de mouillage d'une solution aqueuse de liquide ionique sur un substrat à tube à ailettes en aluminium

Mots-clés: Hystérésis de l'angle de contact; Hystérésis humidifiant; Liquide ionique; Tube à ailettes en aluminium; Caractéristiques de mouillage

1. Introduction

The importance of wetting phenomena can be found in many industrial applications such as in chemical industry (e.g. painting), construction (waterproofing), liquid desiccant and absorption systems (Yamaguchi et al., 2011; Giannetti et al., 2016; Lubis et al., 2016; Giannetti et al., 2017; Varela et al., 2018; Giannetti et al., 2018), distillation columns, flow pattern transition of two-phase flows (Giannetti et al., 2018), and more. For example, in falling film liquid desiccant systems, knowing the wetting properties of a liquid on a solid substrate is of primary importance as the wettability of the flowing solution on the surface dictates the dehumidification/regeneration capacity of the system.

Wetting deals with the study of how a liquid deposited on a solid or liquid substrate spreads out (Ponter et al., 1967). In dynamic wetting processes, the definition can be extended to the study of the wetting properties of flowing films on solid surfaces such as in multiphase-flow devices. The wettability (degree of wetting) can be determined by balancing the effects of the adhesive and cohesive forces, which varies for different types of liquid and/or substrate. However, accurate information about these forces are usually not available. To simplify the computations in

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Nomenclature

A	area, m^2;
d	distance between opening, mm;
D	diameter, mm;
F	flow sensor;
FS	full scale;
g	standard gravity, m•s^{-2};
H	height, mm;
IL	ionic liquid;
n	number of openings, -
P	tube pitch, mm;
R_a	arithmetic mean roughness, µm;
R_p	maximum peak height, µm;
R_v	maximum valley depth, µm;
R_z	maximum height, µm;
RD	relative density hydrometer;
Re	Reynolds number, -
t	opening thickness, mm;
T	thermocouple;
u	uniform stream-wise velocity, m•s^{-2};
V	volume, µL;
w	opening width, mm;
W	wetting/width, mm;
We	Weber number, -
WF	wetting fraction, -
X	IL mass fraction, %.

Greek symbols

δ	average film thickness, m;
γ	surface tension, N•m^{-1};
Γ	mass flow rate per unit width, kg•m^{-1}•s^{-1};
μ	dynamic viscosity, Pa•s;
ρ	density, kg•m$^{-3;}$
σ	surface tension, J•m^{-2};
θ	contact angle, °.

Subscripts

A	advancing;
d	decreasing;
D	dynamic;
f	fin;
h	horizontal;
H	hysteresis;
i	increasing;
LG	liquid-gas;
min	minimum;
pt	plate tilt;
R	receding;
S	static;
SG	solid-gas;
SL	solid-liquid;
t	tube;
ts	test section;
v	vertical;
w	wetted.

falling film models, the working surface is usually assumed to be completely wetted. However, this is usually not the case in experiments as film breakage and dry spots frequently occur in falling film devices (Zhang et al., 2005); thus, without proper calculation of the wetted area and assuming always a complete surface wetting could overestimate the heat and mass transfer performance of gas-liquid contactors. Occurrence of incomplete fin wetting was observed by Jain et al. (2000) in their experimental investigations of a falling film type regenerator. By matching their experimental data to their predicted results, they found that the actual wetted area of the fin available for heat and mass transfer was only 60% of the total fin surface area. Park et al. (1994) associated the errors from their computational results to the assumption of complete fin wetting in their model. According to Pietruschka et al. (2006), a perfect model for predicting the wetting factor is nearly impossible since the wetting of the exchange surface depends on the surface and the solution properties, and the momentum, heat, and mass transfer conditions. Recently, Qi et al. (2013) experimentally investigated the effects of several parameters on the wetted area and film thickness of lithium chloride (LiCl) solution on a single channel internally heated regenerator. Based on their experimental data, they developed a theoretical 3D (air-solution-water) model for the prediction of the wetted area, film thickness, and flow velocity of the falling film. Then, using the same test section from their previous study, they (Qi et al., 2013) investigated the influence of the plate surface temperature on the wetted area and found that the wetted area increased as the plate surface temperature increased especially at low flow rates. In a follow up study (Qi et al., 2014), they developed a new model for the prediction of the wetted area, which showed better agreement with the experimental data compared to their previous model.

Wetting hysteresis is a complex phenomenon that still requires detailed experimental and theoretical investigation. Many articles in the open literature that study about the wetting hysteresis phenomenon have used the concept of contact angle hysteresis to describe wetting hysteresis. For instance, in (de Jonghe and Chatain, 1995; Shanahan, 1995; Jin and Koplik, 1997; Kabov and Zaitsev, 2013; Soolaman and Yu, 2005; Chang et al., 2016) the term wetting hysteresis was used to describe the difference between the contact angles (θ_A and θ_R). Similarly, in Emelyanenko et al. (2004), wetting hysteresis is defined as the difference between cos θ_R and cos θ_A. It can be argued that there is somewhat a misconception about wetting hysteresis.

In general, the wetting characteristics of a falling liquid film on a surface are quite complex and usually require rigorous experimental investigations to fully comprehend. To have a deeper understanding of the wetting properties of a liquid on a solid substrate, intensive studies on its wetting patterns, contact angles, contact angle hysteresis, wetting fraction at different flow rates, minimum wetting rates, critical film thickness, and wetting hysteresis are necessary. Also, there is a need to find liquid desiccants and contact surfaces suitable for liquid desiccant systems especially those with low corrosion and high hydrophilic properties, respectively.

This research is aimed at clarifying the wetting characteristics of a newly developed ionic liquid (IL) desiccant on an aluminum fin-tube substrate, specifically we focus our attention on the visualization of the wetting pattern, measurement of the contact angles and contact angle hysteresis, estimation of the wetted area, determination of the wetting fraction, and analysis of the wetting hysteresis of the solution on the aluminum substrate at various IL mass fractions. This study also aims to clarify the wetting hysteresis phenomenon and to differentiate it from contact angle hysteresis. One highlight of this study is the development of a method for the evaluation of the wetted area and calculation of the wetting fraction based on the experimental measurements. The results can be used to develop a new model or improve available models of the wetting fraction and to improve/optimize the design of internally cooled/heated fin-tube contactor.

2. Experimental apparatus and procedures

In an actual liquid desiccant system, it is difficult to visualize the important phenomena occurring inside its components. In this