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Improvement of the ultrasonic atomization liquid desiccant dehumidification system

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ABSTRACT

Liquid desiccant dehumidification system has received much attention in recent years for its important economic benefits in energy saving of buildings. Furthermore, the specific surface area of desiccant solution can be expanded dramatically by the ultrasonic atomization technology, which generates numerous tiny droplets with diameter about 50 μm. However, the tiny atomized droplets are found to be easily captured by the wall of dehumidifier chamber, resulting in the poor performance of this type of system. In this paper, a new criterion called "droplets suspension rate" together with an optimized design method was proposed to improve the performance of ultrasonic atomization liquid desiccant dehumidification system via optimizing its dehumidifier chamber. Experiments were carried out to verify the improvement, where the dehumidification effectiveness, desiccant consumption rate and the air temperature rise were adopted as indicators to evaluate the performance of the system. The results showed that the performance of ultrasonic atomization liquid desiccant dehumidification system was enhanced significantly and the desiccant consumption was reduced markedly after the improvement. Moreover, the improved system was found to be able to utilize lower-grade desiccant solution. The criterion and the method proposed may build a foundation for the better design of ultrasonic atomization liquid desiccant dehumidification system.

Nomenclature

L	equivalent length, [m]
H	equivalent height, [m]
W	equivalent width, [m]
η	droplets suspension rate
κ	droplets capture rate
G	mass flow rate, [kg/s]
v	velocity, [m/s]
T	time, [s]
ρ	density, [kg/m^3]
t	temperature, [°C]
d	humidity ratio, [$kg_{water}/kg_{dry\ air}$]
μ	dynamic viscosity, [Pa s]
D	diameter of the liquid droplets, [m]
S	horizontal distance, [m]
N	number of droplets
A	area, [m^2]
V	volume, [m^3]
g	gravitational acceleration, [m/s^2]
UADS	ultrasonic atomization dehumidification system
ϕ	dehumidification effectiveness, [%]
ω	desiccant concentration, [%]
LGR	liquid–gas ratio
DCR	desiccant consumption rate, [kg/s]
ATR	air temperature rise, [°C]

Subscripts

ver	vertical
hor	horizontal
l	liquid desiccant
a	air
drp	droplets
in	inlet
out	outlet
avg	average
sur	surface
opt	optimized
equ	equilibrium

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1. Introduction

Liquid desiccant dehumidification system has received much attention in recent years since it can take good advantage of solar energy or the industry waste heat for regeneration [1–3]. These advantages offer important economic benefits in energy saving of buildings [4–8]. The dehumidifier is considered to be one of the most important components of the system since it is the place where the entire dehumidification process happens [9–12]. Due to its significant impact on the system performance, various types of dehumidifiers have been proposed and studied experimentally. For example, dehumidifiers packed with random/structured packings were extensively studied by Gao et al. [11], Fumo and Goswami [13], Longo and Gasparella [14], Liu et al. [15], Moon et al. [16] and Zurigat et al. [17] In addition, to avoid the carryover of desiccant solution, liquid-to-air membrane exchangers were also widely employed as the dehumidifiers in the studies by Abdel-Salam et al. [18], Huang et al. [19], Ge et al. [20,21], and Moghaddam et al. [22] while a new type of wire mesh packings was developed by Kumar et al. [23]. However, the operating costs of these systems were relatively high since a great deal of desiccant solution has to be consumed for good wettability required by the dehumidifier [16,24].

In view of this, Wang et al. [25] proposed a new ultrasonic atomization dehumidification system (UADS) in which the desiccant solution was atomized into tiny droplets by the ultrasonic transducer. The ultrasonic transducer played a great role in increasing the specific surface area of desiccant solution. In this case, the contact area between the humid air and liquid desiccant was enlarged greatly. Analysis of the feasibility of this new system showed that its theoretical dehumidification performance was quite good and the theoretical desiccant consumption was reduced considerably [26]. Bian et al. [27] later established the UADS and studied its performance experimentally. However, the results were not good enough and showed poor consistency with the theoretical study of Wang et al. [25]. The reason for this may have been caused by the improper design of dehumidifier chamber in their system.

Hence, the following issues are to be concerned about in this work:

(1) How to design a proper dehumidifier chamber in the UADS?
(2) How to evaluate the droplets suspension state during the dehumidification process in the UADS?
(3) Is there any relationship between the size of dehumidifier chamber and the system performance-influencing factors, such as the liquid–gas contact time, the liquid–gas contact area, as well as the droplets suspending state in the UADS? What exactly it is?

To address the above issues, this study developed a novel model together with a new criterion called “droplets suspension rate” for optimization design of dehumidifier chamber in the UADS. To verify the model, UADS with a newly designed chamber was built up and relevant experiments were conducted in comparison with the former system [27]. The criterion and the model proposed in this paper may build a foundation for the better design of ultrasonic atomization liquid desiccant dehumidification system.

2. Modeling and optimized design method

2.1. Concept of droplets suspension rate

In the UADS, tiny desiccant droplets are found to be easy to drift [26] and captured by the wall of dehumidifier chamber during the dehumidification process. Once captured, the tiny desiccant droplets gathered together making contact with the humid air in the form of liquid film on the chamber's wall. Consequently, the specific surface area of desiccant solution decreases dramatically, giving a possible reason of the poor performance of the UADS in Ref. [27].

Therefore, this work proposed a new concept called *droplets suspension rate* to evaluate the mass (volume) proportion of droplets that remain suspended (have not been captured by the wall) in the dehumidifier chamber to the entire droplets generated by the ultrasonic transducer during a certain dehumidification period. It is defined as:

$$\eta = \frac{G_{l,\mathrm{drp}}}{G_{l,\mathrm{entire}}} = \frac{V_{l,\mathrm{drp}}}{V_{l,\mathrm{entire}}} \quad (1)$$

where $G_{l,\mathrm{drp}}/V_{l,\mathrm{drp}}$ refers to the mass/volume of the droplets that are still suspending in the chamber, and $G_{l,\mathrm{entire}}/V_{l,\mathrm{entire}}$ refers to the mass/volume of the entire droplets atomized in a certain period.

Meanwhile, a concept named *droplets capture rate*, κ, was proposed to assess the mass (volume) proportion of droplets that have been captured by the wall of dehumidifier chamber to the entire droplets generated during a certain dehumidification period. It is defined as:

$$\kappa = \frac{G_{l,captured}}{G_{l,\mathrm{entire}}} = \frac{V_{l,captured}}{V_{l,\mathrm{entire}}} \quad (2)$$

where $G_{l,captured}/V_{l,captured}$ refers to the mass/volume of the droplets that have been captured, and $G_{l,\mathrm{entire}}/V_{l,\mathrm{entire}}$ refers to the mass/volume of the entire droplets atomized in a certain period.

Combine Eqs. (1) and (2) to gain:

$$\eta = 1 - \kappa \quad (3)$$

It is easy to see that with a higher droplets suspension rate, more desiccant solution will be in contact with the humid air in the form of tiny droplets and the liquid–gas contact area will be expanded considerably. The droplets suspension rate is so significant that it was employed to be one of the criteria in optimizing the dehumidifier chamber of UADS, as discussed in the following chapter.

2.2. Criteria for optimized design

In view of the fact that the tiny desiccant droplets are easy to drift and their initial velocity is quite low [26], the criteria and the optimized design method were developed based on the following assumptions:

(1) The desiccant droplets remain spherical and have no size change during the dehumidification process.
(2) No collision or merging happens among desiccant droplets.
(3) The desiccant droplets are distributed evenly in the planes perpendicular to the air flow direction.
(4) After a transient momentum exchange, the desiccant droplets maintain the horizontal velocity same with the air, namely,

$$v\mathrm{drp,hor} = va \quad (4)$$

(5) Inside the dehumidifier chamber, the air velocity remains constant.

Meanwhile, to make the analysis easier, a rectangle dehumidifier model, as shown in Fig. 1, was set up during the optimization process in this work.

2.2.1. Liquid–gas contact time T_a

Liquid–gas contact time was believed to have significant influence on the performance of dehumidification system [27]. For certain humid air, the longer time it takes in the dehumidifier chamber, the more sufficient it can react with the desiccant solution.