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Concept of dehumidification perfectness and its potential applications

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ABSTRACT

Liquid desiccant dehumidification system, which presents great potential for energy saving in HVAC industry, has drawn much attention in recent years. Various dehumidifiers have been proposed for achieving the better performance and are used to be evaluated by the indicator: dehumidification effectiveness. However, this widely-used indicator is found varying significantly with the operational conditions and cannot distinguish the inherent mass transfer capability of dehumidifiers from the influence of the properties of airstream and desiccant. In view of this, this paper presents a novel concept named dehumidification perfectness, based on the conversion laws of mass and energy, for realizing the impartial evaluation of the inherent mass transfer capability of dehumidifiers, getting rid of the influence from the airstream and desiccant solution. Experimental data from the open literatures was employed to validate the concept and its affecting factors were then discussed. It was found that higher degree of dehumidification perfectness was obtained with bigger/longer effective liquid–gas contact area/time provided by the dehumidifier. Furthermore, with different properties of various dehumidifiers, such as the surface area densities of packing, their dehumidification perfectness was varying significantly. The concept developed here demonstrates promising potentials for comparing, predicting and improving the performance of various dehumidifiers.

1. Introduction

Liquid desiccant dehumidification system has generated considerable research interest in recent years since it is able to remove moisture from the humid air effectively, resulting in the marked reduction of the latent load in air-conditioning systems. Besides, it can make good use of the renewable or low-grade energy such as the solar energy or the industrial waste heat for regeneration [1,2]. These advantages offer great potential in facilitating the energy efficiency of buildings [3–6]. Within the liquid desiccant dehumidification systems, the dehumidifier, where the humid air is dehumidified by the liquid desiccant, is considered to be one of the most vital components [7,8]. Its performance shows profound effect on the overall performance of the entire dehumidification system [9]. Therefore, the investigators have dedicated to developing various types of dehumidifiers, seeking for the better performance. For example, dehumidifiers with counter-flow configurations were extensively studied by Fumo and Goswami [10], Zurigat et al. [11], Mohammad et al. [12]and Mahmud [13] et al. while Liu et al. [14], Gao et al. [8] and Moon [15]et al. conducted detailed investigations on the performance of the dehumidifiers with cross-flow absorbers. Moreover, a new liquid desiccant dehumidification system combined with the ultrasonic technology, i.e. the UADS, in which the desiccant solution was atomized into tiny droplets with the diameter about 50 μm by the ultrasonic transducer and flowing in parallel with the airstream, was proposed and investigated by Wang et al. [16], Bian et al. [17], and Yang et al. [18,19]. However, due to the considerable complexity of dehumidification process, the experimental studies tend to be quite exhausting and time-consuming.

In view of this, a number of models and formulas were established for realizing the fast prediction of dehumidification performance in various liquid desiccant dehumidification systems. For example, Liu et al. [14], Moon et al. [15], Dai and Zhang [20] developed the models for predicting the dehumidification performance of the cross-flow dehumidifiers while models for the rapid prediction of the counter-flow absorbers' performance were built by Abdul-Wahab et al. [21], Chung [22] and Gandhidasan [23] et al. However, although these formulas were found fitting well with their own experimental results, apparent inconsistency has emerged when compared with the experimental data obtained by other researchers. One example is that Liu et al. [14] proposed an empirical formula for predicting the dehumidification performance

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Nomenclature

UADS	ultrasonic atomization liquid desiccant dehumidification system
IDM	the Ideal Dehumidification Model
G	mass flow rate, [kg/s]
t	temperature, [°C]
n	desiccant concentration, [%]
d	humidity ratio, [g/kg $_{\text{dry air}}$]
ϕ	dehumidification effectiveness, [%]
K	dehumidification perfectness, [%]
p	pressure, [Pa]
Mol	molar mass, [g/mol]
h	enthalpy, [kJ/kg]
MRR	moisture removal rate, [g/s]
LGR	liquid–gas ratio
SYST	system type
S.A.D.	surface area density, [m^2/m^3]

Subscripts

ideal	ideal condition
act/exp.	experimental value
a	air
l	liquid desiccant
i	inlet
o	outlet
d	dry air
q	moisture
AT	atmospheric
equ	equilibrium
pred	predicted value
cal	calculated value
(x,y)	dehumidification unit (x,y)

of cross-flow packed towers; notwithstanding the good agreement between the predicted results and the experimental data achieved in their own work, substantial deviation was observed when applying the formulas to Moon's system [15] which adopted the cross-flow packed bed as well. This may due to the fact that these empirical formulas were generally worked out by the method of step-regression with their own experimental data; their physical meaning seems to be unconvincing and unclear [18].

Apart from that, the mass transfer performance of liquid desiccant dehumidification systems was used to be evaluated by the indicator: dehumidification effectiveness in many works [8,10,14,15,19,24]. It is defined as the ratio of the difference between the humidity of inlet airstream and the tested values of the outlet airstream to the difference between the humidity of the inlet airstream and the equilibrium values of the inlet fresh desiccant solution [25]. With higher value of dehumidification effectiveness, the dehumidifier was usually considered to possess better mass transfer abilities, in spite of the flow patterns of the dehumidifiers. This is generally true for counter-flow dehumidifiers where the outlet of airstream is exactly the same location of the fresh desiccant solution's inlet. However, since the air outlets are no longer located at the entrances of fresh desiccant solution in parallel-flow or cross-flow systems where the dehumidification ability of the desiccant solution at the outlet of airstream in these types of systems tends to be weakened significantly due to the temperature rise and concentration drop [14], the airstream may never be able to be handled to the humidity ratio equilibrated to the inlet fresh desiccant solution. Hence, it seems to be unfair and improper to evaluate the mass transfer ability of cross-flow or parallel-flow systems with the dehumidification effectiveness any longer.

In view of this, the following issues are to be concerned in this work:

1. How to realize the impartial evaluation of the mass transfer performance in the parallel-flow or cross-flow dehumidifiers, considering the fact that the dehumidification ability of the desiccant solution at the outlet of the airstream in these systems is weaker than in counter-flow system?
2. Rather than the traditional empirical formulas devised with the step-regression method, is it possible to establish a fast prediction method that has the clear and convincing physical meaning and is of general applicability for various liquid desiccant dehumidification systems, regardless of the flow patterns inside the dehumidifiers?
3. Is it possible to establish an evaluation indicator that is able to evaluate the inherent mass transfer capabilities of various liquid desiccant dehumidification systems, impartially, getting rid of the effects exerted by the properties of airstream and desiccant solution, such as desiccant inlet temperature, desiccant inlet concentration, air inlet temperature and air inlet humidity ratio?
4. Though various measures have been proposed to improve the mass transfer performance of dehumidifiers, how to evaluate how much room is left for the further enhancement of the dehumidification performance of the specific liquid desiccant dehumidifier?

To address the above issues, a novel concept called “dehumidification perfectness” for evaluating the inherent mass transfer capabilities of dehumidifiers with different flow patterns was developed in this work. Then experimental data from the open literatures [8,14,15,18] was employed to validate the concept and effects of the various inlet operational conditions on dehumidification perfectness were also discussed. The concept established in this work is able to evaluate and distinguish influence produced by the inherent mass transfer capabilities of dehumidifiers from the effects exerted by the vapor pressure on dehumidification performance. It presents promising potential applications for improving and predicting the dehumidification performance of various liquid desiccant dehumidifiers.

2. Concept of dehumidification perfectness and its calculation method

2.1. Concept of dehumidification perfectness

In liquid desiccant dehumidification systems, the mass transfer performance was used to be evaluated, regardless of their flow patterns, by the indicators dehumidification effectiveness (*ab*. DE) and the moisture removal rate (*ab*. MRR), as Eqs. (1) and (2) show, respectively:

$$\phi = \frac{d_{\text{i}} - d_{\text{o}}}{d_{\text{i}} - d_{\text{equ}}} \times 100\% \tag{1}$$

$$\text{MRR} = G_{\text{a}} \times (d_i - d_o), \tag{2}$$