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Exergy calculation and analysis of a dehumidification system using liquid desiccant

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ABSTRACT

Liquid desiccant dehumidification is an effective method for extracting moisture from humid air and consumes less energy than conventional methods. Exergy is an essential tool to analyze liquid desiccant dehumidification systems. The problem with current exergy analysis of liquid desiccant dehumidification systems is that the exergy calculation for humid air is inconsistent with the exergy calculation for liquid desiccant. The choice of the dead state is the key issue in exergy analysis. In this paper, the saturated air state of ambient temperature is selected as the ultimate dead state. The ultimate dead state of liquid desiccant is defined by limitation of the infinitely diluted solution that will guarantee the uniqueness of the ultimate dead state in the system and address the previously mentioned inconsistency. The exergy flow in the liquid desiccant dehumidification cycle is also calculated (LiBr aqueous solution is used as an example), and exergy expressed per kilogram of dry air and per kilogram of solute can simplify the calculations. Exergy destruction, a measurement of irreversibility in the heat and mass transfer process, indicates the direction of system improvement.

1. Introduction

Liquid desiccant dehumidification has been proven to be an effective method for extracting moisture from humid air with less energy consumption than traditional methods, especially compared to conventional vapor compression systems [1]. Outdoor air handling units using liquid desiccant have been successfully applied in buildings [2]. Moreover, liquid desiccant dehumidification offers the possibility of efficient utilization of solar energy, waste heat, and other energy-saving sources.

Many researchers have studied the heat and mass transfer between humid air and liquid desiccant. Jain et al. [3] conducted an experimental study on a falling film tubular absorber and a falling film plate regenerator, and then compared the experimental results with predictions from theoretical models. Yin et al. [4] experimentally examined the performance of a packed tower regenerator and dehumidifier. Liu et al. [5] developed a theoretical model of the heat and mass transfer process in a cross flow dehumidifier/regenerator. Abdul-Wahab et al. [6] obtained statistical prediction models for the water condensation rate and the dehumidification effectiveness for structured liquid desiccant air dehumidifier. Besides, numerically fitting descriptions of thermodynamic properties of LiBr aqueous solution are provided in [7–9].

Exergy is a thermodynamic quantity that represents the available energy, and is an essential tool for the design, analysis, and optimization of thermal systems [10]. The selection of the dead state is a key factor in exergy calculation. In liquid desiccant dehumidification system, the dead state of humid air is commonly chosen as the saturated state of outdoor air [11–15]. However, consensus about the dead state of liquid desiccant in the field of HVAC studies has not yet been reached. Existing literature does not provide a direct definition of exergy of liquid desiccant solutions in dehumidification systems. Exergy analysis has been applied to examine liquid desiccant dehumidification system, which mainly focuses on exergy efficiency and destruction in system. Ahmed et al. [14] presented applicable exergy analysis and estimated irreversible losses during the operation of a hybrid air-conditioning cycle, and the irreversibilities in the absorber and the dehumidifier were 24.6% and 24.8% of the total irreversibility rate. Xiong et al. [11] also examined a liquid desiccant dehumidification system using exergy analysis, and a desiccant–desiccant heat exchanger (HE), a hot water-desiccant HE, and a cooling water-desiccant HE collectively contributed 75.9% of the entire exergy destruction. The exergy destructions of dehumidifier and regenerator are only 8.2% and 5.3%. In order to calculate and explain the exergy destruction in liquid desiccant dehumidification system, a consistent calculation method for both humid air and liquid desiccant is needed.

Exergy analyses of solid desiccant dehumidification systems, absorption systems, and desalination systems can be considered as references for liquid desiccant dehumidification systems. Bereche et al. [16] presented a methodology for calculating the exergy of

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Nomenclature

a	activity
c_p	specific heat at constant pressure (kJ/(kg K))
Ex	flow exergy (kW)
ex	specific exergy (kJ/kg)
g	specific Gibbs energy (kJ/kg)
G	mass flow rate (kg/s)
h	specific enthalpy (kJ/kg)
m	molality (kmol/kg of solvent)
M	molar mass (kg/kmol)
n	mole number (kmol)
NTU	number of transfer units
p	pressure (kPa)
R	gas constant (8.314 kJ/kmol)
s	specific entropy (kJ/(kg K))
T	temperature (K)
W	water content (kg/kg solute)
x	mole fraction
y	mass fraction

Greek symbols

ω	humidity ratio (kg/kg)
μ	chemical potential (kJ/kg)
γ	activity coefficient
ϕ	osmotic coefficient
ν	dissociation number, 2 for LiBr

Subscripts

a	air
m	solution given in molality
t	total exergy of liquid desiccant
ph	physical exergy (thermomechanical exergy)
ch	chemical exergy
s	solute
v	water vapor
w	water
0	ultimate dead state

Superscripts

*	restricted dead state
o	standard chemical potential
±	mean quantity for ions of an electrolyte
–	partial mole quantity

a lithium bromide aqueous solution, indicating the necessity of taking into account the activity of the constituents in the chemical exergy calculation. Kanoglu et al. [17] introduced a procedure for the energy and exergy analysis of open-cycle desiccant cooling systems. Lior et al. [18] established and solved equations for the temporal and spatial exergy values and changes in the humid air stream and the desiccant for flow of humid air over desiccants and in desiccant-lined channels. Sencan et al. [19] used exergy to analyze a single-effect lithium bromide/water absorption system for cooling and heating applications. Sharqawy et al. [20] suggested that the most up-to-date thermodynamic properties of seawater are needed to conduct an exergy analysis of desalination systems, demonstrating that the exergy values given by an ideal mixture model are inconsistent with actual data-based results.

It is easy to select ambient temperature and pressure as the dead state for physical exergy. However, selecting the dead state for chemical exergy results in some confusion. The dead state of humid air should be consistent with that of liquid desiccant. However, existing literature concerning exergy analysis of liquid desiccant dehumidification does not provide a direct definition of exergy of liquid desiccant solutions in dehumidification systems. This paper will give a definition of the dead state and a calculation method for the exergy of liquid desiccant. The exergy of LiBr aqueous solution and the exergy flow in a liquid desiccant dehumidification cycle are calculated as examples.

2. Basic definitions

Exergy is defined as the maximum work that can be obtained from a given form of energy using the environmental parameters as the reference state [21]. In dehumidification systems, humid air and liquid desiccant are mixtures, so equilibrium with a reference environment means not only thermal and mechanical equilibrium, but also chemical equilibrium [22]. The restricted dead state of the mixture system refers to the state where only the temperature and pressure match the corresponding environmental values, indicated by superscript *. The ultimate (proper) dead state refers to thermal, mechanical, and chemical equilibrium with the environment, indicated by subscript 0.

For mixtures such as humid air and liquid desiccant, total exergy (ex_t) is the sum of physical (thermomechanical) exergy (ex_{ph}) and chemical exergy (ex_{ch}), written as Eq. (1). Physical exergy, expressed as Eq. (2), is the maximum amount of work released to the restricted dead state as an original fixed composition. Chemical exergy, expressed as Eq. (3), is the maximum amount of work as the mixture reaches chemical equilibrium with the reference environment (the temperature and pressure of the mixture before and after the process are fixed as T_0 and P_0, respectively).

$$\overline{ex}_t(T,P,x_i)=\overline{ex}_{ph}(T,P)+\overline{ex}_{ch}(T_0,P_0,x_i) \quad (1)$$

$$\overline{ex}_{ph}(T,P)=\bar{h}(T,P)-\bar{h}^*(T_0,P_0)-T_0[\bar{s}(T,P)-\bar{s}^*(T_0,P_0)] \quad (2)$$

$$\overline{ex}_{ch}(T_0,P_0,x_i)=\sum_{i=1}^{n}[\mu_i^*(T_0,P_0,x_i)-\mu_{0,i}(T_0,P_0,x_{0,i})]x_i \quad (3)$$

2.1. Exergy of humid air

In HVAC applications, especially for dehumidification systems, humid air is considered to be an ideal mixture of dry air and water vapor. Ambient temperature and pressure (T_0, P_0) are chosen as the restricted dead state, and (T_0, P_0, $x_{0,a}$, $x_{0,v}$) are chosen as the ultimate dead state, $x_{0,a}+x_{0,v}=1$. The total exergy of humid air is written as Eq. (4) [22], in which the first two terms represent physical exergy and the last term represents chemical exergy, $x_a+x_v=1$.

$$\overline{ex}_t(T,P,x_a)=(x_a\overline{c_{p,a}}+x_v\overline{c_{p,v}})T_0\left(\frac{T}{T_0}-1-\ln\frac{T}{T_0}\right)+RT_0\ln\frac{P}{P_0}+RT_0\left(x_a\ln\frac{x_a}{x_{0,a}}+x_v\ln\frac{x_v}{x_{0,v}}\right) \quad (4)$$

Eq. (4) is the definition of humid air in the form of a mole fraction. An alternate version, written as Eq. (5), presents total flow exergy per kilogram of dry air, which is better suited for engineering calculations [22]. At standard atmospheric pressure ($P=P_0$), the first term of Eq. (5) represents physical exergy and the second term represents chemical exergy.

$$ex_t(T,\omega)=(c_{p,a}+\omega c_{p,v})T_0\left(\frac{T}{T_0}-1-\ln\frac{T}{T_0}\right)+R_aT_0\left[(1+1.608\omega)\ln\frac{1+1.608\omega_0}{1+1.608\omega}+1.608\omega\ln\frac{\omega}{\omega_0}\right] \quad (5)$$